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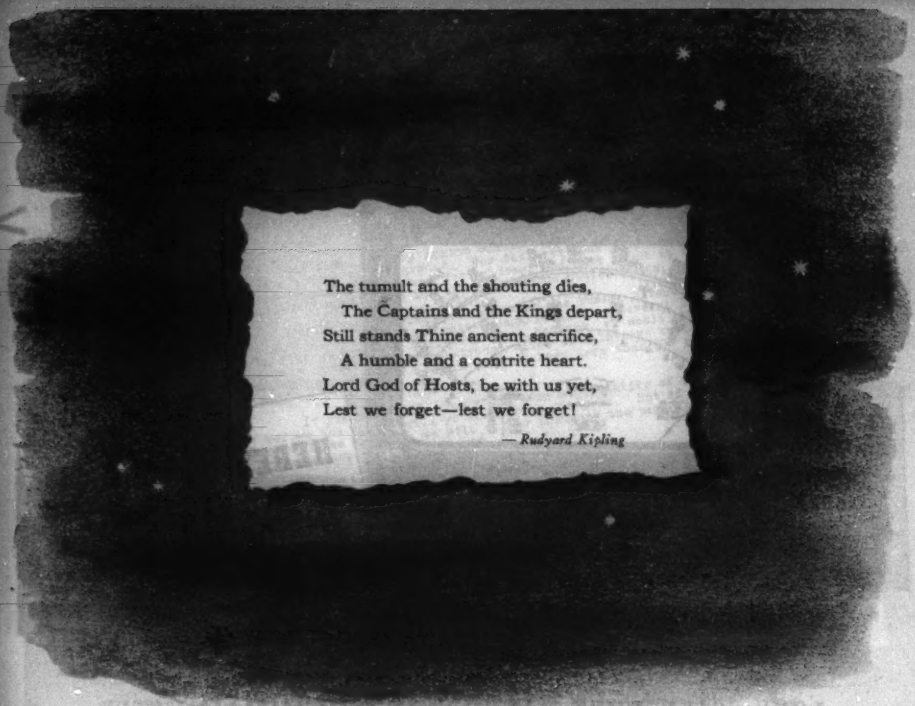
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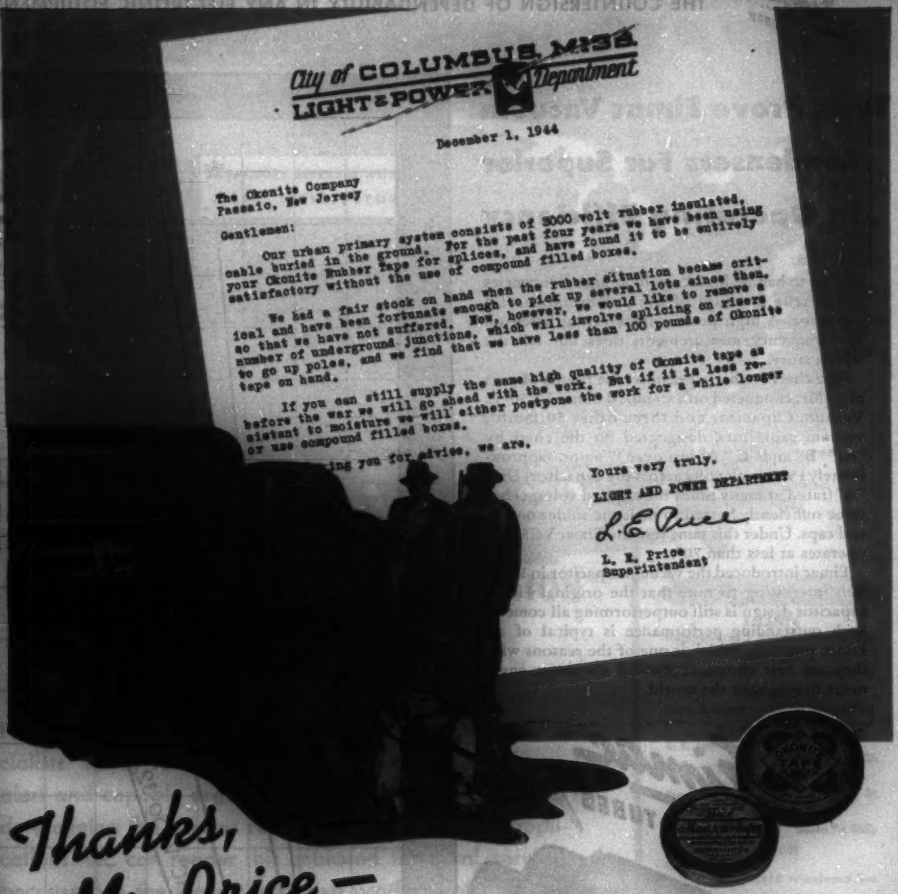
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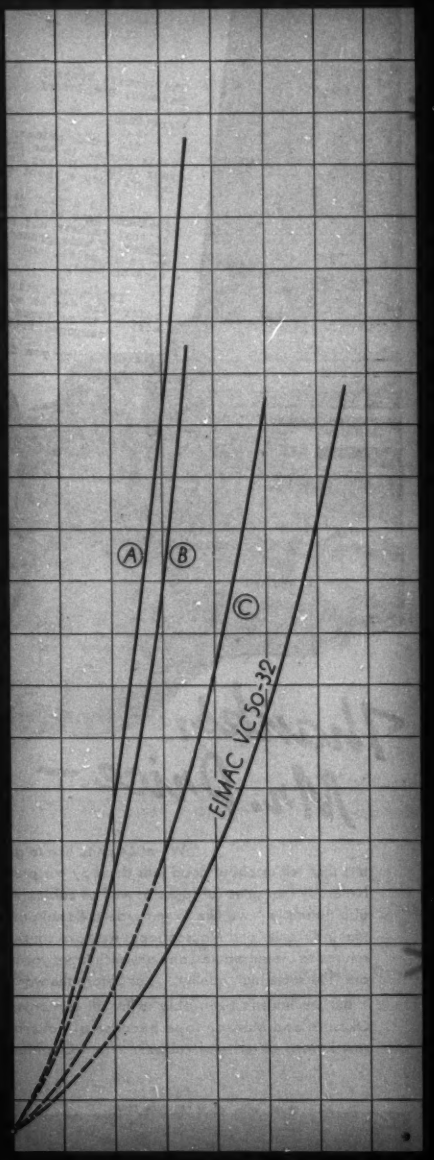

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The Cover: A modern 60-stories-high antenna of KDKA, Pittsburgh, Pa., first established radio station. The 25th anniversary of radiobroadcasting is commemorated in this issue.

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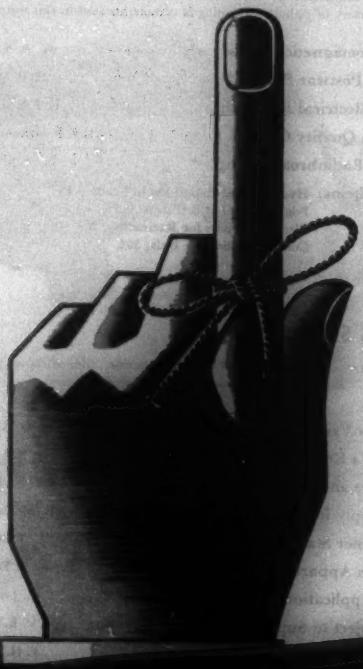

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An Analysis of Electromagnetic Forces

WILLIAM A. TRIPP
MEMBER AIEE

Certain concepts of physics and electromagnetism conflict on several points, chiefly because of the latter's lack of general equations for the reaction of electrical particles. In this article the author introduces a few fundamental electrodynamic concepts and deduces from them some of the commonly used formulas for forces exerted on current-carrying conductors.

ELECTROMAGNETISM, the basic phenomenon of most of the processes involved in the production and use of electricity, is the force which practically moves the civilized world today. It is somewhat surprising, therefore, to find that certain fundamental concepts of electromagnetism do not conform with some of the concepts of general physics. One would think that at this late date the ground had been so thoroughly worked over that any possible points of disagreement would have been eradicated. It is true, of course, that the last few decades have seen such a complete revolution in the field of physics that scientific thought has far outdistanced many of the so-called practical sciences. It is not necessary, however, to embrace the more controversial tenets of the new physics, but only to borrow from some of the concepts which have proved their value and soundness in order to bring to light certain obscurities and inconsistencies which exist in electromagnetic theory.

The difficulty lies in the lack of general equations for the reaction of electrical particles. The engineer usually deals with mass phenomena, for which many formulas are available. The electrophysicist frequently deals with the activity of an individual charged particle but leans heavily upon the equations of the field, which really represent mass action. True, the mass formulas can be written in terms of currents which can be ascribed to the flow of a quantity of electrons, but this merely glosses over the missing elements by means of a change in the units of measurement and does not throw any light on the nature of the effects produced by the individual particles of electricity. A few investigators have offered formulas for the reactions of particles, but this information cannot be found in the textbooks and does not seem to have received general acceptance. One is confronted with the anomalous situation that it is possible to predict with a high degree of accuracy effects due to large numbers of electrons, but it is practically impossible to get the answer when only two particles are involved. The result is that, when a problem is encountered which cannot be reduced to or made to approximate one of the standard forms, such as cases involving so-called end effects, one finds oneself without adequate tools. Even in cases involving standard forms the available explanation is not entirely satisfactory or sound.

The force occurring between conductors carrying currents is one of the most important building blocks of electrical engineering. When the conductors are straight and parallel to each other this force represents one of the simplest geometrical configurations imaginable. If the conductors are of negligible cross section, and the distance between them is negligible compared with their lengths, the force per unit length of either conductor will have the value:

$$F = \frac{2I_1I_2}{S_d} \qquad (1)$$

where:

F = force, in dynes, on each centimeter of either conductor
I_1 and I_2 = the currents in the conductors, in abamperes
S_d = separation between the conductors, in centimeters

The direction of the force is such as to tend to draw the conductors toward each other if the currents are in the same direction, and to separate them if the currents are in opposite directions. This has led to the concept that parallel currents attract if in the same direction and repel if in opposite directions. Up to this point everything could be proved by experiment, but now a conclusion has been drawn that may not represent the facts at all. It is a vastly different statement to say that the conductors tend to be drawn together or forced apart than to say that the currents attract or repel each other. The former statement recognizes that the forces involve the conductors as well as the currents, while the latter completely ignores the presence of the conductors. An error of viewpoint is involved, such as occurs in the explanation of the phenomenon known as "skin effect." It is explained as a crowding of the current to the outer portions of the conductor, and, while everybody who has to deal with this phenomenon knows that, conversely, it really consists of a progressive reduction in current density toward the inner portions of the conductor, the idea of crowding persists in popular parlance.

In the case of parallel currents, if it is the currents which attract or repel, this fact should be capable of experimental proof with the conductors eliminated, as, for example, the streams of electrons which make up cathode rays. A single heavy stream should tend to coalesce into a very fine but dense stream, while two parallel streams should tend to combine into one. Scientists have been working with such streams for many years but these effects apparently have gone unreported, although an actual case involving two streams does not seem to have occurred. It has been suggested, though, along with several other possible arrangements, by some popular writers on the subject. However, beyond a certain point the explanation becomes hazy and the description of the details of the proposed apparatus rather indefinite, with no clear indication that the author had ever tried the experiment himself.

Magnetic effects have been produced under carefully controlled test conditions by the physical movement of charged bodies. These experiments prove that charges in motion with respect to other charges produce magnetic effects, but there is nothing in them to prove that charges experiencing the same motion

William A. Tripp is an electrical engineer for Charles T. Main, Inc., Engineers, Boston, Mass.

(that is, not actually moving with respect to each other) produce any magnetic effect upon each other. There is no ground for the belief that parallel streams of electrons in the same direction, whether as currents in a conductor, cathode rays in a tube, or accumulated charges on a body, attract each other because of a common absolute motion. If they did, it would be a simple matter to set up an arrangement to determine the true motion of the earth through space. The experiments referred to show that man-made speeds are sufficient to produce magnetic effects. When potential is applied to a conductor, current will begin to flow. This *fact* of current flow is transmitted along the conductor with something approaching the speed of light, but the actual *movement* of electrons along the conductor is relatively very slow. It is much like the flow of water in a pipe. If the pipe is full before the water starts to flow, the water will begin to move practically instantly everywhere along the pipe, but it will take some time for a particular drop of water to travel the length of the pipe. Some idea of the speed of electron movement in current conduction will be given in a subsequent paragraph. The important fact is that it is slow enough to be within the range of human experience. Thus, earth speed, such as its rotation, revolution about the sun, and galactic movement through space, should have a ponderable effect, with the result that all the electric meters in the world would be subject to a diurnal and seasonal correction. This would produce a most unhappy state of affairs for the electric utility companies, while careful scientists would be bedeviled eternally with an endless series of corrective measures. Fortunately, nature has arranged things for us better than that.

"UNNEUTRALIZED" PROTONS

All this discussion suggests that parallel currents in the same direction do not attract each other. With conductors carrying currents in opposite directions, there is clearly a relative motion between the electron streams, and the conclusion that the repulsive force results from this condition is logical. This leaves the attractive force to be accounted for between the electrons and the conductors. In electrical conduction, the conductors are assumed to be neutral, that is, composed of ordinary matter consisting of equal amounts of positive and negative electrical particles. The flow of current is assumed to be due to the motion of certain "free" electrons which are present therein and readily mobile under the influence of electrical potential. For every electron thus set in motion there must be a positive charge left behind, so to speak, still bound up in the atoms of the material, and remaining stationary. These may be termed the "unneutralized" protons, and it will be clear that their numerical count per unit quantity of conductor will be the same as that of the moving electrons. The moving electrons in one conductor therefore will be seen to be moving relative to the unneutralized protons in the other conductor, a condition which suggests itself as the seat of the attractive forces. This leads to the following propositions:

1. Like charges in relative parallel motion repel each other.

2. Unlike charges in relative parallel motion attract each other.

COMPONENTS OF FORCE ANALYZED

A full derivation of the actual magnitudes of the forces will be given in subsequent paragraphs. Let it suffice for the moment to say that since the observed forces, as evaluated by equation 1, are proportional to the product of the currents, they are a second-power effect and the individual forces on the particles must be proportional to the square of their relative speeds. Taking the case of the parallel conductors with the same value of current in each, and assuming for the moment that equal currents mean equal electron speeds (certainly true if one conductor is the continuation of the other), if the currents are in the same direction there will be two components of force on each conductor. One will be the force between the moving electrons in the one conductor and the unneutralized protons in the other conductor. The other component will be the force between the unneutralized protons in that conductor and the moving electrons in the other conductor. These two components will be of equal magnitude, and by the second proposition, both attractions. The total force on each conductor then is an attractive force of relative magnitude 2. Clearly there is no force between the stationary protons in the two conductors and, by all the preceding evidence, there is none between the moving electrons. They are moving in the same direction, at the same speed, and therefore not moving at all with respect to each other. Assume, now, that the current in one conductor is reversed. There will be the same two attractive components, as before, since proposition two considers only relative motion and does not establish preference as to direction. But a new component enters because of the relative motion of the electron flows in the two conductors. It will have a magnitude due to the same number of moving charges as the proton–electron force but double the velocity since the electron streams are moving past each other. By the square of twice the velocity, its relative magnitude will be 4, and by proposition one it will be a repulsion. The net force between the conductors thus will be the combination of an attraction of magnitude 2 and a repulsion of magnitude 4, or a net repulsion of magnitude 2. Reversing the current in one conductor consequently produces an equal force but reverses its direction, a result entirely in agreement with experience and equation 1.

Application of this concept should lead to a clearer explanation of some of the more obscure electromagnetic phenomena. A case of this nature is found in the "pinch" effect, observed in electric furnaces used to melt material by passing current through the charge. It has been found that when the charge becomes molten, if the current that is passed becomes too great, the charge tends to constrict or pinch in upon itself and reduce in cross section. The usual explanation, offered almost identically by different authorities, is that the current can be considered as a group of filamentary currents distributed over the cross section of the charge, and that by the attractive effect observed when currents are flowing in the same direction the filaments of the material of the charge are drawn together. This explanation always has seemed faulty, as it directs attention to the filamentary currents as the seat of the force, but requires that this force somehow appear on the material of the charge. The implication is that the electrons pulled or pushed (as suggested by one reference) the material of the charge inward as they themselves were drawn toward the center. As this is a case of electrical conduction, it would seem that the electrons are fairly free, not being bound very strongly to the atoms. It is therefore inconceivable that the electrons could pull any of the material along with them. It *is* conceivable that they would bump into atoms as they were drawn inward and in that way could be said to push the charge inward, but, with the turbulence in the furnace and the viscosity of the melt, it probably would be a rather slow process. Even the smallest atoms would have some 1,840 times the mass of the electrons that were trying to push them. Considered, however, in the light of the foregoing propositions, the phenomenon is adequately explained. With the flow of current through the melt, there will be "unneutralized" protons in the melt and, by the second proposition, there will be attractive forces between the electron streams and these protons. The net attraction on each is directed toward the common center of cross section, and the result is a pinching effect. By a process of mutual attraction both the charge and the current are drawn in.

There is no doubt that this effect is present also in ordinary metallic conduction, showing up as a magnetostrictive effect in the material and a tendency of the current to crowd toward the center of the conductor. The actual amount of crowding would be very slight, however. Electrostatic forces soon would arise as a result of displacement of electrons and stop its further progress, for the protons cannot travel inward and maintain the

electrostatic balance as in the molten charge in the furnace. Electrostatic forces really are of tremendous magnitude, much larger than generally is realized, and a very slight displacement of electrons would be sufficient to counterbalance the electromagnetic forces of even a heavy current flow. This is truly a case of crowding, entirely distinct and different from "skin" effect.

The case of the parallel conductors does not lend itself immediately to the numerical solution of the forces between particles moving parallel to each other as there are nonparallel velocities present. It must be recognized that the particles in any portion of one conductor are moving toward or away from the particles in those portions of the other conductor which are not directly opposite. These "in-line" velocities may be expected to have an effect, which they do. Recourse may be had to a case where the in-line velocity forces cancel out, such as the circular loop carrying a current, with an electron located at the center of the loop and moving in the plane of the loop. This is shown in Figure 1.

The regulation electromagnetic analysis of this problem states that there is a magnetic field set up by the current I, the magnitude of which is $B=\frac{2\pi I}{R_c}(\mu=1)$ gausses at the center of the loop, and that the charge e_1 is acted upon by a force $F=Q_1V_1B$ dynes or $F=Q_1V_1\frac{2\pi I}{R_c}$, the direction being downward in the figure. Since the current in the loop actually consists of a stream of electrons moving in a counterclockwise direction (this necessary change in viewpoint as to direction of motion being the result of an unfortunate guess on the part of our scientific forefathers), then the force on electron e_1 must result from the relative motion between it and the electrons moving in the loop. It is possible to skip the intervening mechanism of the magnetic field and trace this force back to the reaction due to each electron of the current in the loop.

Taking any electron, such as e_2 in the loop, the relative parallel velocity between e_1 and e_2 will be $V_2+V_1\cos\alpha$, and the force resulting therefrom will be $\frac{Q_1Q_2(V_2+V_1\cos\alpha)^2}{R_c^2}$. This function for the force is arrived at by recognizing that the magnitudes of electromagnetic forces are evaluated in terms of the product of the currents involved and the inverse square of the distance of separation. From considerations previously discussed, this force will be a repulsion directed along the line joining the two electrons. The total net force F on electron e_1 will be the summation of all the individual forces due to all the electrons of the loop current. These individual forces are combined most readily if they are evaluated in terms of the same directional components, say a vertical component and a horizontal component. Recognizing that the current I must consist of a number, n_2, of electrons per unit length of the loop, moving with the average velocity V_2 such that $I=n_2Q_2V_2$, the vertical component of the force on e_1 due to the group of electrons in any small length dS_c of the loop, will be

$$\partial F_y=\frac{Q_1Q_2(V_2+V_1\cos\alpha)^2}{R_c^2}\cdot\cos\alpha\cdot n_2\partial S_c$$

$$=\frac{n_2Q_1Q_2}{R_c^2}(V_2^2\cos\alpha+2V_1V_2\times\cos^2\alpha+V_1^2\cos^3\alpha)\partial S_c$$

or since

$$S_c=R_c\alpha,\quad \partial S_c=R_c\partial\alpha$$

then

$$\partial F_y=\frac{n_2Q_1Q_2}{R_c}(V_2^2\cos\alpha+2V_1V_2\cos^2\alpha+V_1^2\cos^3\alpha)\partial\alpha$$

and

$$F_y=\frac{n_2Q_1Q_2}{R_c}\int_0^{2\pi}(V_2^2\cos\alpha+2V_1V_2\times\cos^2\alpha+V_1^2\cos^3\alpha)\partial\alpha$$

$$=\frac{n_2Q_1Q_2}{R_c}\left[V_2^2\sin\alpha+2V_1V_2\left(\frac{\alpha}{2}+\frac{\sin^2\alpha}{4}\right)+V_1^2\left(\sin\alpha-\frac{\sin^3\alpha}{3}\right)\right]_0^{2\pi}$$

$$=\frac{n_2Q_1Q_2}{R_c}\left[2V_1V_2\frac{2\pi}{2}\right]$$

$$=\frac{2\pi n_2Q_1Q_2V_1V_2}{R_c}=Q_1V_1\frac{2\pi n_2Q_2V_2}{R_c}$$

A similar analysis for the horizontal component of this force can be carried out. Its summation for the complete loop will be found equal to zero. There are other forces which can be identified as being present. These are: the force resulting from parallel motion between the electron e_1 and the unneutralized protons in the loop, and the forces due to in-line velocities between this electron and both the electrons and the unneutralized protons in the loop. It will be found that the summation of each of these forces for the entire loop also will be zero. In other words, the vertical component just evaluated represents the complete net electromagnetic force on electron e_1 due to the current in the loop. That is, $F=F_y=Q_1V_1\frac{2\pi n_2Q_2V_2}{R_c}$ and since $n_2Q_2V_2=I$, as explained above, then $F=Q_1V_1\frac{2\pi I}{R_c}$, which is the value given by the regulation electromagnetic analysis. From the correctness of the formula thus derived, it may be inferred that the original premise for the force due to the parallel relative velocity between any two particles is correct. For the geometrical configuration of the case considered this was given as $\frac{Q_1Q_2(V_2+V_1\cos\alpha)^2}{R_c^2}$. In general terms it may be written as

$$F_x=\frac{Q_1Q_2V_x^2}{S^2}\qquad(2)$$

where

F_x = force, in dynes, between moving particles
Q_1 = charge, in electromagnetic units (abcoulombs), on particle number one
Q_2 = charge, in electromagnetic units (abcoulombs), on particle number two
S = distance, in centimeters, between the particles
V_x = parallel relative velocity of the particles in centimeters per second

The line of the force is coincident with the line joining the two particles, and its direction is such as to constitute a repulsion if the charges are of the same sign and an attraction if they are of different signs. In this connection, it is worthy of note that the direction as well as the magnitude of the net total force for the case shown in Figure 1 was determined by a strict mathematical analysis, without recourse to any right-hand screw relationships or three-fingered perpendicularities, so difficult to rationalize and remember. It is to be noted that equation 2 gives positive values for repulsive forces and the net force for the case shown in Figure 1 came out positive for the direction which was assumed without prejudice, albeit with foreknowledge. This directional determination is a simplification in itself.

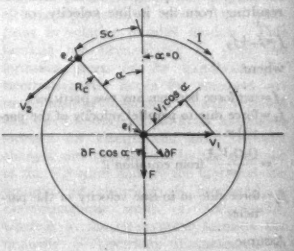

Figure 1. Diagram showing a circular loop carrying a current

R_c = radius of the loop, in centimeters
I = current flowing in the loop, in abamperes (clockwise)
Q_1 = charge, in electromagnetic units (abcoulombs), on electron at center of loop
Q_2 = charge, in electromagnetic units (abcoulombs), on any electron of current I
V_1 = velocity of electron e_1, in centimeters per second, to the right
V_2 = velocity of electron e_2, in centimeters per second, counterclockwise
α = angle which line between e_1 and e_2 makes with a selected zero position. This zero position is taken perpendicular to V_1 counterclockwise
F = force on electron e_1, in dynes

The evaluation of the forces due to in-line velocities now can be accomplished by taking a case where these effects do not cancel out, and separating from it the force due to the parallel velocities in accordance with equation 2. Such a case is found in the arrangement, previously discussed, of two infinitely long straight conductors, of negligible cross section, parallel to each other, as shown in Figure 2.

There will be a variety of forces present in this arrangement. Considering a unit length of conductor 1 at its midpoint, it will experience a force because of each of the following reactions:

1. The relative motion between the moving electrons in the given length of conductor 1 and all the moving electrons in conductor 2.

2. The relative motion between the moving electrons in the given length of conductor 1 and all the "unneutralized" protons in conductor 2.

3. The relative motion between the "unneutralized" protons in the given length of conductor 1 and all the moving electrons in conductor 2.

These three reactions can be evaluated in terms of the forces between the particles involved. Moreover, since we are concerned only with the attractive or repulsive force between the conductors, that is, the force perpendicular to their length, it is necessary to consider only the component of any of these individual forces perpendicular to the conductor.

The force between any two particles will be made up of two parts, that resulting from the parallel velocity and that resulting from the in-line velocity, or

$$f = f_x + f_y$$

where

f = net force between any two particles

f_x = force due to parallel velocity of the particles

$$= \frac{Q_1 Q_2 V_x^2}{S^2}$$ from equation 2

f_y = force due to in-line velocity of the particles

Assume

$$f_y = k \frac{Q_1 Q_2 V_y^2}{S^2}$$

where

k = a constant

V_y = the in-line relative velocity of the particles, in centimeters per second

Then

$$f = \frac{Q_1 Q_2}{S^2}(V_x^2 + kV_y^2)$$ for the general case

For particular cases:

Let

f_1 = the force between two electrons according to reaction one

Then

$$f_1 = \frac{(-Q_1)(-Q_2)}{S_d^2 + S_2^2} \quad [(V_1 \cos\alpha - V_2 \cos\alpha)^2 + k(V_1 \sin\alpha - V_2 \sin\alpha)^2]$$

$$= Q_1 Q_2 \frac{\cos^2\alpha}{S_d^2} [(V_1 - V_2)^2 \cos^2\alpha + k \times (V_1 - V_2)^2 \sin^2\alpha]$$

Let

f_2 = the force between an electron in conductor 1 and a proton in conductor 2 according to reaction two

Then

$$f_2 = \frac{(-Q_1)(Q_2)}{S_d^2 + S_2^2} [(V_1 \cos\alpha)^2 + k(V_1 \sin\alpha)^2]$$

$$= -Q_1 Q_2 \frac{\cos^2\alpha}{S_d^2} [V_1^2 \cos^2\alpha + kV_1^2 \sin^2\alpha]$$

Let

f_3 = the force between a proton in conductor 1 and an electron in conductor 2 according to reaction three

Then

$$f_3 = \frac{(Q_1)(-Q_2)}{S_d^2 + S_2^2} [(V_2 \cos\alpha)^2 + k(V_2 \sin\alpha)^2]$$

$$= -Q_1 Q_2 \frac{\cos^2\alpha}{S_d^2} [V_2^2 \cos^2\alpha + kV_2^2 \sin^2\alpha]$$

Let

f = the total force on unit length of conductor 1 due to all three reactions with particles in any small length ∂S_2 of conductor 2

Then

$$f = n_1 f_1 n_2 \partial S_2 + n_1 f_2 n_2 \partial S_2 + n_1 f_3 n_2 \partial S_2$$
$$= n_1 n_2 (f_1 + f_2 + f_3) \partial S_2$$

Let

f_y = the perpendicular component of f

Then

$$f_y = n_1 n_2 (f_1 + f_2 + f_3) \cos\alpha \, \partial S_2$$

But

$$\frac{S_2}{S_d} = \tan\alpha$$

Then

$$\partial S_2 = \frac{S_d \partial\alpha}{\cos^2\alpha}$$

Then

$$f_y = n_1 n_2 \left(Q_1 Q_2 \frac{\cos^2\alpha}{S_d^2} \right) [(V_1 - V_2)^2 \times \cos^2\alpha + k(V_1 - V_2)^2 \sin^2\alpha - V_1^2 \cos^2\alpha - kV_1^2 \times \sin^2\alpha - V_2^2 \cos^2\alpha - kV_2^2 \sin^2\alpha] \cos\alpha \frac{S_d \partial\alpha}{\cos^2\alpha}$$

$$= \frac{n_1 n_2 Q_1 Q_2}{S_d} [-2V_1 V_2 \times \cos^2\alpha - 2kV_1 V_2 \sin^2\alpha] \cos\alpha \, \partial\alpha$$

$$= -\frac{2n_1 n_2 Q_1 Q_2 V_1 V_2}{S_d} [\cos^2\alpha + k \times \sin^2\alpha \cos\alpha] \partial\alpha$$

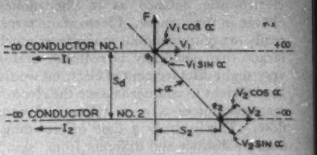

Figure 2. Diagram showing two infinitely long straight conductors

I_1 = *current, in abamperes, in conductor 1 (positive direction to the left)*

I_2 = *current, in abamperes, in conductor 2 (positive direction to the left)*

Q = *charge on any electron or proton, being negative for electrons and positive for protons, in abcoulombs*

n_1 = *number of moving electrons or unneutralized protons per unit length (centimeter) of conductor 1*

n_2 = *number of moving electrons or unneutralized protons per unit length (centimeter) of conductor 2*

V_1 = *average velocity, in centimeters per second, of moving electrons in conductor 1 (positive direction to the right)*

V_2 = *average velocity, in centimeters per second, of moving electrons in conductor 2 (positive direction to the right)*

S_d = *distance of separation, in centimeters, between the conductors*

S_2 = *distance, in centimeters, of any point on conductor 2 from the midpoint of that conductor*

α = *angle which the line joining the midpoints of the conductors make with the line joining the midpoint of conductor 1 and any point on conductor 2 (midpoints of the two conductors assumed opposite each other)*

Let

F = the total perpendicular force on unit length of conductor 1 due to all reactions from entire length of conductor 2

Then

$$F = \int_{\alpha=-\frac{\pi}{2}}^{\alpha=\frac{\pi}{2}} f_y$$

$$= -\frac{2n_1 n_2 Q_1 Q_2 V_1 V_2}{S_d} \int_{\alpha=-\frac{\pi}{2}}^{\alpha=\frac{\pi}{2}} [\cos^2\alpha + k \times \sin^2\alpha \cos\alpha] \partial\alpha$$

$$= -\frac{2n_1 n_2 Q_1 Q_2 V_1 V_2}{S_d} \left[\sin\alpha \frac{\sin^2\alpha}{3} + \frac{k}{3} \sin^2\alpha \right]_{\alpha=-\frac{\pi}{2}}^{\alpha=\frac{\pi}{2}}$$

$$= -\frac{2n_1 n_2 Q_1 Q_2 V_1 V_2}{S_d} \left[\frac{4}{3} + \frac{2k}{3} \right]$$

Since

$I_1 = n_1 Q_1 V_1$ and $I_2 = n_2 Q_2 V_2$

Then

$$F = -\frac{2I_1 I_2}{S_d} \left[\frac{4}{3} + \frac{2k}{3} \right]$$

But F is known to be equal to $-\frac{2I_1I_2}{S_d}$ (from equation 1 and negative because the currents have been assumed in the same direction and the force is an attraction).

Then

$$-\frac{2I_1I_2}{S_d}\left[\frac{4}{3}+\frac{2k}{3}\right]=-\frac{2I_1I_2}{S_d}$$

and

$$k=-1/2$$

The force between particles due to relative in-line velocity is, then,

$$F_y=-\frac{Q_1Q_2V_y^2}{2S^2} \tag{3}$$

where

F_y = force, in dynes, between moving particles
Q_1 = charge, in electromagnetic units (abcoulombs), on particle number one
Q_2 = charge, in electromagnetic units (abcoulombs), on particle number two
S = distance, in centimeters, between the particles
V_y = in-line relative velocity of the particles in centimeters per second

For the general case, equations 2 and 3 may be combined, giving

$$F=F_x+F_y$$
$$=\frac{Q_1Q_2}{S^2}\left[V_x^2-\frac{V_y^2}{2}\right] \tag{4}$$

In order to determine the direction of the force it is necessary merely to use the appropriate positive and negative signs of the charges on the particles and call the repulsive direction positive.

The negative sign of the V_y term in equation 4 may be a little startling as it means that when electrons are moving toward or away from each other there is an attractive force set up, while there is a repulsive force set up when electrons are moving toward or away from protons. What may be particularly surprising is that the force does not change sign with change in direction of motion. For instance, it is always a repulsion between electrons and protons, just the opposite of the parallel velocity effect. Interpreting this with respect to its physical significance, it means that when a conductor is carrying a current there is a longitudinal tensile stress set up in it, an internal force tending to stretch it. It has been shown that there is a magnetostrictive force set up under this condition which tends to contract the conductor radially. Its counterpart in the form of an axial stretching effect consequently may not be so surprising. This stretching effect does exhibit itself and has been noted but has gone unexplained. For instance, in the case of the pinch effect discussed previously, certain of the standard references include a statement to the effect that there is also a stretching effect in the material of the charge in the furnace which tends to elongate it in the line of current flow, but do not offer any explanation. It will be clear, however, that for any conductor of finite length there will be more electrons on one side of any given length of the conductor, except the very middle section. By equation 3 or 4 there will be a preponderance of force from that direction, which, by inspection, is a force directed away from the middle of the length of the conductor, or a stretching effect. Furthermore, if the formulas indicated that the force changed direction with change in direction of relative motion, it would predicate erroneously a net force tending to move the entire melt in the furnace in one direction, or any other conductor carrying current for that matter. Such a result would be contrary to observation and record. In other words, the formulas derived in this article are in accordance with observations.

"STRETCHING" EFFECT

It should be noted also that there is a "stretching" effect on the current itself. It might have been expected that the stretching effect on the conductor would be balanced, so to speak, by a compressive effect in the current, but this is not the case. It is found that the conductor and the current are stretching each other lengthwise just as they are compressing each other crosswise. The stretching effect in the current is, in effect, an internal voltage within the length of the conductor which, nevertheless, cancels out over its entire length. This, again, is to be expected, otherwise it would constitute a voltage with respect to the entire circuit and conflict with Ohm's law.

At an earlier point in this analysis, reference was made to the velocities involved in the flow of current in conductors. It was stated that these velocities are small in terms of ordinary experience. This can be demonstrated readily. According to the accepted concept of conduction, the flow of current consists of the movement of the free electrons associated with the atoms of the material of the conductor. Assume a piece of Number 12 American wire gauge copper wire carrying a current of ten amperes (=one abampere) such as occurs daily in home lighting circuits. A centimeter of this wire weighs about 0.294 gram and an atom of copper weighs about 1.06×10^{-22} gram. There are, therefore, about 2.78×10^{21} atoms in a centimeter of Number 12 copper wire. If each atom contributes one electron to the current flow, there are about 2.78×10^{21} electrons in motion in each centimeter. Each electron has a charge of 1.60×10^{-20} abcoulomb. Since an abampere is defined as a flow of one abcoulomb per second, and $I=nQV$, $1=2.78\times10^{21}\times1.60\times10^{-20}\times V$, V must be about 0.0225 centimeter per second.

This speed may seem amazingly slow, particularly in view of the rate at which the *fact* of current flow is transmitted along a conductor, which is something close to the speed of light, or nearly 3.00×10^{10} centimeters per second. It can be said that the voltage vector establishes itself at this tremendous rate and thus gets the current going, but this does not explain just what the voltage vector or electrical field is. It is left to the imagination of the individual to visualize how this vector follows the conductor and is confined thereto and directed along it, even through the intricate convolutions of a piece of electric machinery, while all the time he knows that potential effects appear across insulating materials as well as along conductors.

It would seem that the voltage vector is established by the creation of an electrostatic field along the length of the conductor by reason of a disturbance of the normally uniform distribution of electrons. It already has been stated that electrostatic forces are really tremendous, much larger than generally is recognized. This is because it is difficult to produce large unbalances of electrical charges on account of the great magnitude of the resultant effects. Something will usually let go before the unbalance becomes very great, and we have become accustomed to think in terms of the smallness of the unbalance instead of the relatively huge effect caused by the small unbalance. Some idea of this relationship is gained by considering the relative magnitude of electrostatic and electromagnetic forces between particles. Equation 2 gives the electromagnetic force between two electrons in relative parallel motion. This formula has been shown to yield the formulas given in the handbooks for electromagnetic forces for standard arrangements of conductors. It will be noted that this formula is similar to the handbook formula for electrostatic force between charges, differing from it by the presence of the V_x^2 term and by the fact that the quantity of electricity is measured in electromagnetic units or abcoulombs, whereas in the electrostatic formula the quantity of electricity is measured in electrostatic units or statcoulombs. The ratio of these two units is 3×10^{10} which is numerically equal to the velocity of light, so that the relative velocity would have to be equal to the velocity of light for the electromagnetic force to be equal to the electrostatic force. However, it has just been shown that electric currents involve velocities which are probably only a small fraction of a centimeter per second. Since the force is proportional to the square of the velocity, the comparative puniness of electromagnetic force can be imagined. And yet this is the force which practically moves the civilized world today.

In view of this relationship of magnitudes, it is evident that it would not require much of a variation in the con-

centration of free electrons along a wire to establish the necessary potential gradient. In the number 12 American wire gauge copper wire considered earlier, the resistance is about 1.62 ohms per 1,000 feet under standard conditions. This means that to cause one abampere (ten amperes) to flow, 16.2 volts per thousand feet, or 0.000530 volt per centimeter, direct current, is required. The rate at which energy is consumed per centimeter of wire length in causing this current to flow is $10 \times 0.000530 = 0.00530$ watt. As has been stated, there are about 2.78×10^{21} electrons per centimeter involved, moving at an average velocity of about 0.0225 centimeter per second. If there is an average force of f dynes acting on each of these electrons, the energy consumption would be $2.78 \times 10^{21} \times 0.0225 \times 10^{-7} \times f$ watt per centimeter. Since this must be equal to the above value of 0.00530 watt per centimeter, the average force on each electron must be equal to 8.48×10^{-16} dyne.

This force may be considered a result of a greater concentration of electrons on one side than on the other. This would mean that the concentration of electrons in the wire increases toward the negative end. The rate at which this concentration would have to vary along the wire may be calculated by straightforward electrostatic methods, and comes out something of the order of 1.55×10^{-11} per cent per centimeter when the concentration is 2.78×10^{21} electrons per centimeter, or a variation of about 4.31×10^{9} electrons per centimeter. Another way of looking at this is in terms of the spacing of the electrons. At the density of 2.78×10^{21} electrons per centimeter, the spacing is about 2.28×10^{-8} centimeter between electrons and differs by only 1.55×10^{-11} per cent from the concentration in the next centimeter. This small spacing and the small variation required in it to produce the necessary potential along the wire make it clearer how current can go through the many convolutions and contortions required of it and still permit the voltage vector apparently to be directed simply along the conductor in any machine that can be built by human hands.

This digression on the subject of current conduction has been included because it seemed to bear some relation to the general subject of electron reactions. In ordinary cases, where the arrangements correspond reasonably closely to standard forms, the relationships may be worked out by means of the usual engineering methods for which the formulas are to be found in the handbooks. The propositions advanced in this analysis should be of practical assistance, however, in the solution of unusual and obscure cases, and cases involving so-called end effects and other configurations which cannot be reduced to standard forms. It has been customary to break nonstandard arrangements up into parts which individually can be made to approximate some standard form, but too great a dependence on the accuracy of this method must be cautioned against. It is better to apply the formulas for the reactions of the individual electrons, which can be used to good advantage, as has been shown in some of the cases discussed. Recognition of the necessity for relative motion in order to produce electromagnetic effects, and segregation of the parallel and in-line velocities, should lead to the explanation of many effects and the observation of others. In a broad sense, it may be expected that electromagnetic effects can be ascribed to many cases which involve apparently static charges, but where these charges, although stationary with respect to the observer or the observer's "mass" viewpoint, actually may not be stationary with respect to other charges in the neighborhood.

The Engineer in the Postwar Period

R. P. MEILY

TWO FACTS stand out clear and sharp against the postwar years ahead: First, engineers will have unprecedented opportunity; and second, industry should start now to conserve technical talent in every way and help train new engineers as quickly as possible.

These conclusions are inescapable. Engineers will be scarce because:

1. When the war ends, industry will have fewer competent engineers than in 1942, and none in training.

2. It will take time to bring returning engineers up to their former efficiency.

3. Colleges will not graduate engineers for several years.

4. There will be no flow of engineers from war-born industries battling to stay in business.

On top of these conditions will be the pressing commercial urge to freshen and market former standard products as quickly as possible while new products are still in the making. With a huge reservoir of technical knowledge ready to be put to work, practically all of these new products will require more engineering than ever before in order to be competitive. These approaching conditions in industry all add to make a period of unusual opportunity for good engineers.

A shortage of qualified engineers in the postwar period is foreseen in this article, in which industry is urged to aid itself. In particular, industry is urged to train a number of young engineers each year regardless of business conditions.

The problem industry will face after the war has its roots in the early 1930's. During the depression many experienced engineers were released by industry. No young engineers were being brought in for training as replacements, resulting in a present void in the ranks of engineers in the age group now 30 to 40 needed for wartime engineering. Had this group been in training and available in 1942, industry would have spared itself a great deal of money and time that went into training programs of all sorts which often turned out to be costly makeshifts. Design, development, and production would have gotten off to a quicker start with less waste of manpower and materials. Industry has had to bid in the open market for engineers and then train those engineers on the job—and this at a time when there were very few engineers available.

Engineers found their services also were being sought eagerly by Government as well as by industry. A large portion of the young engineers had reserve officers' training and were immediately commissioned. Those with engineering backgrounds were naturally attracted to the services, thus adding to the shortage of available men. Industry then was forced to employ a large number of young graduate engineers and train them on the

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job. This eventually failed as practically all of those under 29 finally were inducted into the service.

ENGINEERING RANKS DEPLETED

At present, industry is undermanned in engineering talent, both as to quantity and quality. The fault is not the engineer's, but lies in the fact that industry allowed ten years to pass during which too few engineers were in training. The engineers in industry are generally over 40. The void in the age group 30–40 never will be filled, and the lack of men in this bracket will continue to be felt for the next 20 years, reaching the maximum in about 1955.

Although nothing can close this gap, the future flow of new engineers over the years matches industrial requirements nicely; that is, fewer older, experienced engineers are required than younger, inexperienced men. The small group of seasoned engineers will fill the executive and supervisory positions to guide and safeguard the younger engineers. However, a gap in the training of engineers as in 1929 and 1939 becomes more serious to industry as age increases. There will be relatively few engineers in the age group 50–65 between the years 1955–65. The deficit must be made up from the ranks of engineers 45 years old, who may be lacking in experience and judgment. To prevent a repetition of this condition, industry should bring into its organization each year a basic number of young engineers from each graduating class regardless of the state of business. This provides minimum insurance.

In the interest of strengthening and maintaining adequate engineering personnel for the immediate postwar period, it would be well for industry to analyze the probable demand and the supply of engineering talent.

Many young engineers will probably elect to remain in the service of the Government. There is ample evidence of the necessity of maintaining a large Army and Navy, which will require much engineering talent of high order. New weapons and techniques will become more and more technical, and the higher the degree of mechanization, the more specialized must be the people who are to design, develop, manufacture, operate, and service the equipment.

In parallel with a scarcity of technical help during the immediate postwar period, industry faces a large pent-up demand for manufactured goods. Industries in a position to supply such goods at once will skim the cream of the business. But by advertising and other means, the public has been led to expect marvelous product changes all along the line; and this public will no longer be satisfied with a new 1942 model automobile, refrigerator, or radio. It will be necessary, therefore, for industry to make good quickly on some of the promises.

To bring out a new or improved product has generally been a long process of development and experiment followed by the creation of specialized machinery and manufacturing processes, all requiring much time. The urge will be to accomplish all of these things quickly; and the people who do these things are engineers. The fact that things must be done quickly, in itself, means larger engineering staffs.

Of necessity, new products will be more highly mechanical and technical than prewar products. The public looks forward to finding ingenious principles used in war applied to industrial, commercial, and home uses.

In addition, the public will not only be product conscious, but price conscious; perhaps not at first, but increasingly so as more goods become available. This means a highly competitive situation, requiring the best in engineers all along the line.

This trend will affect the sales forces of industry when they are expanded from their present wartime skeleton. New products will call for more highly specialized sales and service training. Many of these men must have engineering training. Indeed, it would seem that industry will not be able to get by in terms of services previously rendered.

There are three principal ways in which industry can help itself:

1. Keep the good engineers already in its service contented; and use these engineers at their highest skills. Industry has already taken steps to keep its engineers. Such factors as seniority, wage reviews and raises, and pensions work in this direction.

2. Industry must recruit engineering forces from outside sources and institute training programs which will quickly make these engineers productive. In attracting new engineering talent from outside sources, industry finds itself in a highly competitive position. The well-established industry with accepted products will have the advantage, but it will have to offer pay rates commensurate with ability and opportunity and all the usual standard employee benefits. Engineers will be scarce, and many are going to be money conscious.

3. Industry must look to the colleges for young engineers when the colleges again graduate engineers. It may be three or four years or more before the colleges can be counted upon for such men in normal numbers. When graduates are available, a liberal number should be placed in training which will fit them for service in the shortest possible time. The young graduating engineers can be discounted for the immediate postwar period, because there will be so few of them in the next four or five years, perhaps longer, that their presence will have little influence in the over-all result.

The immediate problem which industry faces with regard to engineers is made more serious by the current desire of engineers to change jobs. The unrest can be attributed to the fact that industry is taking every means at its disposal to build up a strong engineering force in preparation for postwar activity which creates the job market. At the same time, engineers in strictly war industry are looking for more secure postwar opportunity. Many, because of salary stabilization, are also hoping to better themselves by a change. All things considered, it appears that the immediate future of the engineer is for more recognition and increasing responsibility.

Hydroelectric Expansion in France

By expanding her network of hydroelectric plants and increasing production of existing plants, France hopes to compensate, in some measure, for the acute coal shortages now paralyzing her vital industries. French engineers have three programs for expansion of the system.

Although the first program, that of 1938, never was completed entirely, dams constructed under its provisions are now supplying France with 1,200,000,000 kilowatt-hours of energy. Two more large dams, l'Aigle and St. Etienne de Cantales, may be completed by the end of the year, while a third, Genissiat, cannot be finished before the end of 1948. The 1941 program provided for construction of 49 dams supplying 5,250,000,000 kilowatt-hours. Only the Thués Dam in the Pyrenees is nearing completion, but work is under way on 18 smaller dams which will furnish 2,000,000,000 kilowatt-hours. The two most important, Bort-les-Orges (400,000,000 kilowatt-hours) and Chastang (540,000,000 kilowatt-hours), both in the Massif Central, may be opened in October 1949. Still in the blueprint stage are the 46 dams provided by the 1945 program, including the giant Donziere Montdragon on the Rhone River, which will supply France with 5,600,000,000 kilowatt-hours. Engineers hope that dams completed by the end of 1945 will supply over 1,000,000,000 kilowatt-hours to the Massif Central and 360,000,000 to the Pyrenees, thereby saving 1,000,000 tons of coal. It is estimated that four months after the opening of these plants, enough energy will have been supplied to compensate fully for the coal used in their operation.

In order to utilize these plants to capacity, France must also put up a new network of high-voltage transmission lines. Three years will be required to build 1,500 miles of high-voltage wires carrying from 60 to 220,000 volts.

One Facet of Naval Electrical Research

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Research is a significant element in the field of naval electrical engineering as it is in all scientific fields. In this article the author takes cognizance of the general subject but concentrates on one phase of naval electrical research; that concerned with the adaptation of shipboard equipment to wartime conditions, a period of unlimited demand and limited supply.

THE TERM "RESEARCH" is one of the most imaginative of the words forming our scientific and electrical vocabulary and as such lends itself to many definitions and interpretations. It is, however, our immediate concern to examine one particular facet or concept of this word, and its relationship to the scope of naval electrical engineering.

For this purpose it is convenient to think of research in terms of its cause and effect; the cause as the need for a new type of service material, or necessity for improvement of an old material, and the effect as the reduction to practice through research, development, and standardization. The picture as a whole may be likened to an Archimedean spiral where the center point represents the initial inception of the problem and where the line of the spiral represents that research work necessary to advance the problem to the development point. The line then carries us through the final performance stage to standardization and a Navy specification representative of the minimum satisfactory performance level for shipboard material. Service experience determines if and when further research is necessary. When this is the case the spiral of research progress continues in a repetitive pattern but it encompasses an ever-expanding field of knowledge.

This is a concept of research in its broadest aspect since it is inherently and inseparably related, through the foundation it builds, to the successive and progressive steps of development, standardization, and operating experience. The cycle thus defined depends for its initial, and for each succeeding, impetus on that research that evaluates performance of materials and equipment, that seeks out and develops new materials, that measures and simulates service performance in the laboratory, and that visualizes future problems in time for their solution before the emergency arises. In other words, research properly planned and conducted develops new concepts. The new concepts enable one to visualize and anticipate future needs.

OUTSIDE RELATIONSHIPS

The laws of physics recognize no limiting boundaries that allocate new materials and equipment to one particular field of application. Thus it is that research, and especially research of the more basic type, is of universal interest and provides common ground over which the engineer or scientist must pass in traveling from the field of domestic or industrial endeavor into the more specialized sphere of military requirements. It is true that specialized needs, where they are sufficiently important, establish research trends in the private laboratory and lead to the development of new and significantly different materials. It is, however, also a fact that ability to accelerate development of special naval material or equipment sometimes depends on the commercial background available and on scientific advances.

Figure 1. Outside relationships

A. Peacetime condition
B. Wartime condition

In speaking of naval electrical research the picture would not be presented in its true perspective if this research were assumed to have nothing in common with that of other branches of the Armed Forces. In some cases the problems are identical and research for one provides the answer for both. This thought has its foundation, in fact, where certain Bureaus of the Navy and Services of the Army are working jointly in their laboratories on common problems. This work grows out of, and forms the basis for, Joint Army–Navy standardization work that is well advanced and has to its credit numerous *JAN* specifications.

It is, therefore, apparent that research progresses most effectively and rapidly through a thorough knowledge of the purpose it serves in the fields of development and standardization and through its common-interest linkage with industrial laboratories where answers in the form of new and needed materials already may be in the making.

SCOPE

The scope of research is inherently that of the problems requiring solution. The limitation to the degree of perfection attained is the limitation engendered by our working materials and our ability to mold them into a most effective end result. Thus, the starting point in electrical naval research is the matériel phase, where, through research intended to produce new or improved materials or through ingenious design combinations, it is possible to bring about a performance objective. The likelihood of achieving this end depends on the severity of the service requirements, commercial availability, scientific talent, and long-range planning.

Material as such lends itself to the generic classifications of dielectrics, conductors, and structural parts so combined as to present the most effective assembly of the dielectric and conductive units. Design, arranged chronologically, passes through the successive steps of:

1. Component part or individual unit.
2. Equipments composed of individual units.
3. Systems made up of equipments.
4. Co-ordination of systems.
5. Warcraft designed by utilizing most effectively a combination of these steps.

Starting initially with the broader perspective we may evaluate the over-all picture and subject to review any of its parts for purposes of improvement through research.

The research scope can be defined more concretely by specifying the major service requirements for which equipment and materials must be developed when they are not available. These numerous service conditions include the following representative and more important factors:

(*a*). High humidity.
(*b*). Excessive temperatures.
(*c*). Shock and vibration.
(*d*). Extremes in operating conditions (from northern latitudes to tropical or torrid zones).
(*e*). Necessity for maximum reduction in weight and space for equipment.

Essential substance of an address presented at a meeting of the AIEE Worcester Section, March 9, 1945.

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These conditions must not only be effectively dealt with, but the end product should be simple in design, possess a long service life, and in many instances be required to perform unusual functions.

Thus far our discussion has dealt with generalizations relating to "concept," "outside relationship," "scope," and "special problems" that are found in the electrical naval research field. It is the purpose now to amplify these ideas and in this manner to emphasize some of the patterns that are found useful in thinking of naval research in the electrical-engineering field.

SPECIFIC ASPECTS OF RESEARCH

On considering research we may note a complete cycle consisting of the research, development, standardization, and operation phases of, so to speak, a rectangular spiral.

The steps then repeat if and as necessary, depending on the needs of the service. Each advancing step in the pattern represents a composite of the background plus what is made possible of achievement because of this background.

From Figure 1 it is apparent that two spheres of activity can be considered as distinct and separate but that a common ground or common linkage exists to join the two. This common area is at all times the more basic research, but with less frequency it extends into specific application improvements such as increase in

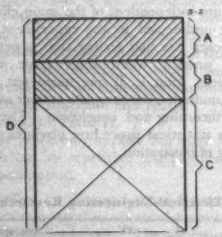

Figure 2. Special problems

A. Size reduction; apparent development
B. Size reduction; real development
C. Optimum equipment size
D. Standard frame size

heat and flame resistance of electrical insulation which represents a development that is commonly useful throughout electrical industry. It has been accelerated in this instance, however, by the urgent shipboard needs for heat- and flame-resistant dielectrics.

It should be of interest to engineers to think of the scope of research in terms of an algebraic equation where it is possible to define as quantity A the required service performance and quantity B as the matériel available to meet the needs of A. In this case the end performance C must be equal to or greater than B/A. If $B/A<1$ research is necessary. Performance A as a whole might be summed up as the life period under accelerated aging conditions where ruggedness is adequate and where deterioration of the insulation has not taken place to the extent that a

Figure 3. Glass jewel used as instrument bearing

failure is likely to occur. This resolves itself into a problem of the adoption of a truly indicative accelerated aging test which is one of the most difficult things to accomplish as it must be correlated over long periods of time with control samples that are subjected to normal full-lifetime tests.

These tests, as an expression of service conditions and operating requirements cover

1. Life (accelerated aging).
2. Moisture resistance.
3. Vibration and shock resistance.
4. Heat and flame resistance.
5. Fungus resistance.
6. High electrical characteristics.
7. Special functional requirements.
8. Oil resistance.
9. Space and weight resistance.

Passing to performance B it will be seen that the characteristics of material and equipment are measured by the test standard adopted for actual service simulative operation and, as previously stated, if C is not greater than one, then research and development are indicated. This is undertaken through experimentation in new materials or equipment-design improvements in order to achieve the necessary end result. Performance C is this end result.

The manufacturing industry must, in order to accomplish production results, arrange for fabrication on a production-line basis. This production in some of the more common equipment means that the same machinery-frame size will be used from a fractional part of this frame-size capacity up to 100 per cent of the frame rating (Figure 2). This will be repeated when the next step in frame size is reached. Where space and weight warrant the change it is necessary through naval development to reduce the frame size by the amount A. This may be termed apparent development. If, however, it is possible to reduce further the frame size of the equipment by the amount B through utilizing a newly developed heat-resistant insulation while retaining the same rating, we have entered into and completed a phase of real development.

CONTRIBUTING FACTORS

Naval electrical research has been described thus far in terms that are general in character. Perhaps the word "philosophy" would define the approach more accurately. Subsequent paragraphs offer brief, pertinent comment on a few of the other subjects involved in electrical research. The diversity of these subjects serves to emphasize further the scope and the research interest that this field comprises.

Fungus. The part fungus plays in electrical research is an important one. The types of fungus are numerous as experiences in the South Pacific have shown. Fungus eats up the electrical insulation and in some cases reduces the nominal 20-year-life period to a few days. The problems engendered by this condition are manifold. They consist of finding effective fungicides or of developing insulation that is inherently fungicidal in character, as well as developing, in the laboratory, service simulative testing procedures. Presence of moisture has been found to be important in supporting the growth of fungus. Hence the normally important problem of moisture-resistant shipboard equipment and material takes on an added significance where climatic conditions are

Figure 4. Magnet-wire insulation

such as to encourage fungus growth. Our studies in this connection comprise a study of the effect of different fungicides on various fungus cultures, while at the same time retaining good electrical properties in the material.

Glass Jewel and Vibration Test. A large number of electric indicating instruments are used aboard naval ships where the conditions of continuous vibration and intermittent shock tend to reduce the accuracy seriously by attacking the instrument bearing, one of the most vulnerable points in the instrument design. These bearings formerly were imported natural sapphires, but during the war emergency the industrial field developed synthetic sapphires as well as specially treated glass jewels to meet the needs of the Armed Forces. Much has been learned of jewel performance as a part of the electric-

Figure 5. Arc-test apparatus

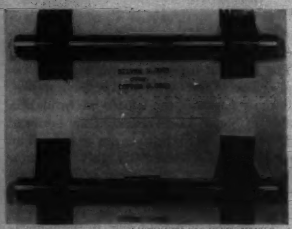

Figure 6. Copper- and silver-plated insulating plastics

instrument design and much of the information has been made available by testing on the vibration-test stand. The particular jewel bearing illustrated in Figure 3 is glass and is slightly larger in actual size than a pinhead.

The electric indicating instrument of which this jewel bearing is a part is tested on a vibration machine. The frequency and amplitude of the vibration are adjustable up to 2,000 cycles per minute and 1/16-inch or 1/8-inch total travel. The movement of the mounting plate that holds the test sample is such as to simulate that existing aboard a ship or plane. It is possible by adjustment of the frequency and amplitude to observe the performance of the test sample at its natural period or resonance condition.

Mica. Mica is a dielectric material that has been invaluable for electrical applications requiring inorganic materials. It has been used for a number of years but the demand for this type of insulation is still practically undiminished. World War II in no way reduced the requirements for electrical purposes but, instead, brought to the fore the fact that even more use must be made of materials available during a period of critical shortage in order to supply the quantities desired, and that more accurate measurements must be devised for determination of electrical quality. In the past, color has been one of the criteria used to select mica quality for electrical applications. It now has been determined through the use of more accurate methods of measurement that color in itself may not be truly indicative of performance limitations of the material. The answer which has developed along these lines has been the result of joint research work on the part of the Armed Forces and outside laboratories. This is a demonstration of the results of research that have been useful in providing a wartime answer by the reduction of the critical status of electrical insulating materials through refined measurement methods and consequent use of greater quantities of the available material.

Magnet Wire. Figure 4 is an illustration in applied form of an insulating film which has been subjected to thousands of hours of heat endurance in order to determine its operation limitations. While the cracks that are observed are not in themselves an accurate measure of failure, they are a true indication of the approaching end of useful life if the end of life is defined in terms of low dielectric strength or low insulation resistance at high-humidity conditions. Research has been extensive in the direction of increased life for insulating varnishes that are required to operate at excessive temperatures, high humidities, and exposure to oil and grease. There is also the problem of considerable mechanical dimensional change in the electric machinery occasioned by the extremes of high operating temperatures and low temperatures while idle. This magnet-wire illustration is a specific application of what might be termed a particular type of synthetic resinous varnish applied in thin film form. Much work has been and is being done on magnet-wire insulation as it forms the basis for electric-machinery design and the continued dependability of this machinery aboard ship where it is vital to the effectiveness of the vessel as a combatant unit.

Application of Statistical Analysis to Electrical-Engineering Research. Table I shows an apparently simple tabulation of numerical values that is potentially more spectacular in its significance in research and the extension of the research horizon than any of the material manifestations that previously have been discussed. This particular table is a summarization of test data taken with a particular type of test machine and representative of a certain product of two manufacturers. The test problem was to measure the relative quality of the two products on several test machines of identical designs. The engineer's attack on such a problem would be to tabulate extensive data by repetitive testing and then to analyze the information for significant variation in performance as indicated by a measure of the number of failures. The mathematician, however, observes that a multiplicity of variations occur simultaneously to effect the final results and to the extent that it is beyond the capacity of human physical conception to separate effectively the significant values.

He observes, for instance, after consultation with the research engineer that, for the particular test illustrated, the following factors vary simultaneously:

1. Variation in the manufacturer's product.
2. Variation in testing machines.
3. Variation in test results due to difference of mounting location on the test machine.

There are added variations over and above the main effects such as factors 1, 2, and 3, which result from interactions between these factors. These, when they exist, are independent of the main effects. If left undetected in the experiment the researcher has that feeling that is persistently present when data have been analyzed; that is, if one more test had been conducted the complete answer would be forthcoming and conclusive. The use of this statistical procedure obviates such feeling of frustration.

Table I. Application of Statistical Analysis to Electrical-Engineering Research

Position	I (A)	I (B)	II (A)	II (B)	III (A)	III (B)	IV (A)	IV (B)	Average (A)	Average (B)
1	42.13	22.79	60.00	39.23	56.79	50.77	45.00	36.27	50.98	37.26
	32.46		49.62		53.78		40.64		44.12	
2	56.79	33.21	50.77	36.27	56.79	39.23	63.44	45.00	56.95	38.43
	45.00		43.52		48.01		54.22		47.69	
3	39.23	22.79	68.61	33.21	53.73	26.56	54.76	22.79	54.08	26.34
	31.01		50.91		40.14		38.78		40.21	
4	56.79	30.00	67.21	26.56	60.00	36.27	53.73	30.00	59.43	30.71
	43.40		46.88		48.14		41.86		45.07	
5	30.00	33.21	45.00	42.13	47.87	53.73	47.87	47.87	42.68	44.24
	31.60		43.56		50.80		47.87		43.46	
Average	44.99	28.40	58.32	35.48	55.04	41.31	52.96	36.39	52.83	35.39
	36.69		46.90		48.17		44.67		44.11	

	S_x^2	DF	M_x	F
Total	6377.1980	39		
Companies (C)	3038.3976	1	3038.3976	169.679**
Machines (M)	796.0864	3	265.3621	14.819**
Positions (P)	234.8221	4	58.7055	3.278*
$C \times M$	111.0565	3	37.0188	2.067
$C \times P$	1218.4119	4	304.6029	17.011**
$M \times P$	763.5436	12	63.6286	3.553*
$C \times M \times P$	214.8799	12	17.9067	

* Significant. ** Highly significant.

Figure 7. Explosion-proof electric-equipment testing chamber

The net result in this instance demonstrated a consistent difference in quality between the two products and a more marked effect on one product for one particular mounting location although a consistently more severe test condition for both products for this same test location on the machine.

Arc-Resistance Analysis. A more complex application of the statistical-analysis procedure shown in Table I involves second-, third-, fourth-, and fifth-order interactions where interactions are defined broadly as the number of result changing forces that are working simultaneously to produce a composite end result. This is illustrated in Table II.

This procedure applies not only to research but to repetitive test problems in standardization.

Arc Test. Figure 5 shows the test apparatus employed to obtain the results for the statistical analysis. The arc resistance of a material or the resistance of a material to tracking is very important in many applications in electric equipment. Numerous methods have been proposed and finally one has been adopted by general usage. This method consists of an arc of ten milliamperes from a 15-kv transformer between electrodes 0.32 inch apart. The arc is applied intermittently to the surface of the material until a conducting path is formed on the material as indicated by the transfer of the arc from the air to the material.

Although this method has been in general use for 10 to 15 years, a recent test in a number of laboratories on identical materials indicated that the variation in results between laboratories was greater than the variation between materials.

Closer study of the method used in the various laboratories disclosed a number of factors which may contribute to the lack of reproducibility and the significance of this test procedure.

Plated Plastic. Figure 6, when considered in connection with Figure 5 depicting arc resistance of plastics, probably appears in the light of a paradox. The rods shown are insulating plastics with copper- and silver-plated films made up experimentally to determine the possibilities existing in using a molded insulation shape such as an instrument case with the shielding as an integral part of the case. It also may have possibilities as a reflecting surface in lighting fixtures. This latter was given some consideration during the critical-supply status of metals. This plating of thermoplastic materials (those softening when heated) is more simple than for the samples illustrated which are molded from the thermosetting resins.

Flame Test. The flame-test method for testing flame resistance of dielectrics has been developed in order to evaluate performance characteristics accurately. This particular test is very familiar to engineers engaged in the design of cable. It is based on the measured and constant electrical input to the heater coil which, in combination with the sparking arrangement, will provide information showing time for ignition of the cable sheath and burning time. In a truly flameproof cable this burning time represents only that period for which the thermal capacity of the cable sample will cause combustible gases to be given off and ignited after removal of the heating source. In other words, the higher temperature necessary for burning the gases is maintained for a time by the thermal capacity or stored heat of the test sample and not by a sample that supports combustion.

Explosion-Proof Electric-Equipment Testing. Figure 7 does not represent an execution chamber as it might appear at first sight. The figure is a dummy used in conjunction with an investigation to determine, in the installation of electric equipment in shipboard spaces where gasoline or other explosive vapors are present, whether a safe level could be found where the hazard did not exist. The dummy was kept at body temperature and was moved about the compartment to simulate movement of shipboard personnel. The effect on the explosive vapor level or the explosive vapor–air concentration then was measured at different heights. The tests were conducted at the Navy portion of the Engineering Experiment Station in Pittsburgh, Pa. In addition to this specific work the shipboard requirements for explosion-proof electric equipment have been developed as a result of research work at this laboratory. Such explosion-proof equipment in itself represents quite a broad field of investigation.

A partial birdseye view, or, if you will, one facet of a many-sided picture has been presented. This view should indicate, rather than actually locate, the parameters of electrical naval research. There

Table II. Arc-Resistance Analysis

		C_1						C_2					
		E_2			E_3			E_1			E_3		
		H_1	H_2	H_3	H_1	H_2	H_3	H_1	H_2	H_3	H_1	H_2	H_3
B_1 F_1	T_1	— —											
	T_2	— —											
B_1 F_2	T_1												
	T_2												
B_2 F_1	T_1												
	T_2												
B_2 F_2	T_1												
	T_2												

Five Main Effects	Ten First-Order Interactions	Ten Second-Order Interactions	Five Third-Order Interactions	One Fourth-Order Interaction
(C)	C×E E×B	C×E×H C×B×F	C×E×H×B	C×E×H×B×F
(E)	C×H E×F	C×E×B E×H×B	C×E×H×F	
(H)	C×B H×B	C×E×F E×B×F	C×E×B×F	
(B)	C×F H×F	C×H×B E×H×F	C×H×B×F	
(F)	E×H B×F	C×H×F H×B×F	E×H×B×F	

(C) Electrode condition cleaned or uncleaned.
(E) Electrode mechanical condition.
(H) Humidity condition.
(B) Type of binder.
(F) Type of filler.

are many aspects of the work that have not even been approached, and this is especially true of that portion maintained in the confidential or secret classification for security reasons. A very few of the many important and interesting things that form a part of the total picture are indicated in the five following examples:

1. The design and installation of a short-circuit test station which will make available current of 100,000 amperes three-phase alternating current, 450 volts or 50,000 amperes, 250 volts direct current. The approximate maximum timing period for each is eight cycles.

2. The subject of electronics which is a field within itself and is far beyond the scope of the present discussion.

3. The study of electric-propulsion systems for different types of warcraft and representative of one of the phases of electrical research having a broad engineering aspect.

4. A program for the preservation of inactive ships which is a most significant phase of naval research with particular reference to the optimum conditioning that should be maintained in order to prevent deterioration in quality of the electrical insulation. This preservation program is a major postwar consideration.

5. The problems arising out of loss of sources of supply for raw materials used in electrical applications, such as tin, rubber, nickel, and the limited quantities of home materials available, where a shortage is created by wartime increase in amounts required for other than electrical purposes. This factor imposed a severe burden on, and at the same time, stimulated electrical research in the Navy.

This article will have served its purpose if it is thought provocative to the extent that it conveys an idea of the scope and magnitude of problems encountered in naval research. The picture as presented is admittedly only a small part or one facet of a many-sided total and is necessarily a viewpoint that primarily relates to shipboard material. It has, however, been the objective throughout the presentation to express it in the common language of research which links together the members of the electrical-engineering profession regardless of their immediate field of application.

Fog Dispersal at British Airfield

A squadron of bombers took off from an airfield in England in December 1944 when the visibility had been cut to about 100 yards by a fog blanket. Returning from a successful mission, they landed safely when the visibility of the area was only 50 yards. One of aviation's worst enemies—fog—had been demonstrated to be impotent. How this seemingly impossible feat was accomplished is told by A. C. Hartley, technical director, Britain's Petroleum Warfare Department, in the September 1945 issue of *Civil Engineering*. Actually, the runway is converted into a huge brazier whose heat lifts fog in the area over and adjacent to the landing strip.

This operation, developed by British engineers, meteorologists, scientists, and pilots, is called "Fido," standing for fog investigation dispersal operations. In a race against time for the lives of Allied pilots, many experts were brought together, and charged with finding a solution to the perplexing problem, sparing no cost. The objective was to clear of fog a space 1,000 yards long by 150 feet wide to a height of 100 feet, 500 yards of the cleared space to be in the approach and 500 yards on the runway.

Research and experiment went on simultaneously. The methods considered included the use of supersonic waves, electrical discharges, absorption of moisture by chemicals, drying by refrigeration, and outdoor air-conditioning apparatus. From the outset, however, the dispersal of fog by heat promised the greatest success. Fog chambers were erected and large-scale heat-producing installations assembled in fog-ridden districts while Royal Engineers constructed and manned a special mobile installation to be sent wherever fog was reported.

The first success came November 4, 1942, when on Moody Down, Hampshire, a fog of 50-yard visibility was cleared by petroleum burners in an area 200 yards square to a height of 80 feet. The same day an even denser fog was cleared at Staines, down wind of a line of braziers burning hundreds of tons of coke. Parallel experiments proved petroleum more successful than coke, though it produced more smoke. It lit up quicker, involved less manpower, and easily could be piped to the site by linking the countrywide network of pipe lines.

By January 1943, experimental large-scale runways had been constructed to which the Fido team hastened whenever they received special fog warnings—usually in the small hours of the morning. It was discovered that if the heat of the atmosphere could be raised seven degrees Fahrenheit the fog disappeared. This heat is provided by a continuous line of petroleum burners installed parallel to, and some distance from, each side of the main runway. The height of the clearance depends upon the wind and the moisture content of the fog. In extreme conditions, such as cloud or sea fog and high winds, it is difficult to get good clearances up to 100 feet, but in calm weather with radiation, fog clearances of more than 500 feet have been obtained.

Standard fog-dispersal installation consists of three main portions—burner lights, pumping and distribution, and storage. On the initial light-up, much smoke is created, but this quickly clears as the petroleum vaporizes. In normal conditions, the fog can be cleared in ten minutes. It has been cleared in six minutes. When intersecting runways are crossed, a burner pipe sink flush with the ground is necessary to avoid obstructing the aircraft. This is supplied by a separate vaporizing unit. The main fuel-handling pumps are six gasoline-engine-driven centrifugal pumps connected to the supply main from the storage tanks. The petroleum is stored in steel tanks. The installation is manned by one Royal Air Force sergeant, three corporals, and 17 aircraftsmen. It is estimated that "Fido" used up 100,000 tons of gasoline in two and one half years—6,000 gallons per aircraft landed.

The first experimental operational installation was erected on a Pathfinder airfield in February 1943, though it was not tested out in the fog until July 17, 1943, when visibility fell to between 100 and 200 yards. Fido restored full visibility on the runways for 1,300 yards. An aircraft took off and landed four times, and Fido's future was assured. It was being established on a number of airfields in eastern and southern England, including the Suffolk rescue station, where hundreds of lame and disabled planes, American as well as British, were brought in.

After months of experiment, Fido was brought into operational use on November 19, 1943. On that day, four Halifax bombers landed successfully on returning from the Ruhr, when the surrounding visibility of the airfield was only 100 yards, because ten minutes after Fido had been lit, visibility on the runway increased to the equivalent of from two to four miles. Since then more than 2,500 Allied aircraft have landed safely—often in dense fog—with crews of more than 10,000 airmen.

About 500 men composed the Fido team, including scientists, a departmental staff of about 50 Royal Engineers, who had the distinction of making the first fog clearance in Hampshire, about 40 Royal Air Force ground staff, engineers, and contractors' men. The Bomber Command loaned experienced pilots and meteorologists.

Statistical Methods in Quality Control

V. Variations to Be Expected in Sampling

This article discusses the chance variations to be expected in observed averages, standard deviations, and so forth, when the quality of a product is measured by samples.

WHENEVER we take a random sample of articles from a batch of product and measure them for some quality characteristic, we do not expect the results to be exactly the same as for the entire batch. The smaller the sample, the more widely may the observed results differ from the true. It can be shown that the magnitude of expected sampling errors (differences between sample values and true values) varies inversely as the square root of the number of articles in the sample.

Take as a particular example the plate current of a vacuum tube. In preparing to manufacture the tube, the producer sets up a production process involving materials, machines, and workmen. There results a complex system of causes, each element contributing to the variations that

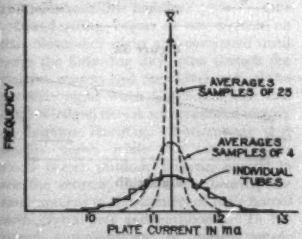

Figure 1. The effect of sample size on the distribution of sample averages

will be observed in the measured values of plate current for the individual tubes. If each of the causes of variation continues to have the same probability of contributing a given effect, the quality with respect to plate current may be said to be controlled in the technical sense. The cumulative effect may be represented by an overall frequency distribution such as is shown in Figure 1.

As indicated in an earlier article of this series, this frequency distribution may be regarded as a statistical representation of the entire production process and may be described by such statistics as the average, $\bar{X}'$, the standard deviation, σ', and the fraction defective, p', the proportion falling outside the specified limits. It is always helpful to keep in mind that behind the scenes there exists some such frequency distribution with some definite set of statistics ($\bar{X}'$, σ', p') which represent the process at any one time.

Suppose we had such an idealized controlled process. Then, so long as the process remains the same, we can predict on a probability basis just how the results of, say, samples of 100 tubes, samples of 25 tubes, or samples of 4 tubes would behave; how these results would differ from the corresponding true distribution curve.

To do this, we find it convenient to express the collective plate current measurements for a sample of n tubes in terms of these same simple statistics: the average, $\bar{X}$, standard deviation, σ, or the fraction, p, of the total observations that fall outside the specification limits.

The solid curve of Figure 1 represents the distribution of plate current values for individual tubes, and the dotted curves indicate the distributions to be expected for averages of samples of 4 and samples of 25. From this it is seen that the larger the sample, the more closely may the observed sample average be expected to approximate the true average, $\bar{X}'$, of the process, the spread being inversely proportional to the square root of he sample size.

This, perhaps, may be seen more clearly from Figure 2, in which the distribution is tipped over on its side and the measurement scale drawn vertically. In Figure 2 we consider successive tubes or successive samples of tubes coming from such a process. For successive individual tubes practically all of the measured values may be expected to fall within the band $\bar{X}' \pm 3\sigma'$. In like manner the observed values of sample averages ($\bar{X}$), for successive samples of n tubes will fluctuate around the *true* value for the distribution curve representing the process. The figure indicates, for example, the range within which *practically all* (theoretically 99.7 per cent) of the averages for samples of stated size will fall under these controlled conditions. The dotted lines shown on the figure are determined from the relation

Limits for sample averages ($\bar{X}$) =

$$\bar{X}' \pm 3\frac{\sigma'}{\sqrt{n}}$$

We can say, for example, "*If* the process is controlled in the foregoing sense, and has an average, $\bar{X}'$, and a standard deviation, σ', then *practically all* the individual observed values will fall within the band $\bar{X}' \pm 3\sigma'$, *practically all* averages of random samples of size four will fall within a band only one half as wide, and for samples of 25 only one fifth as wide.

Similar charts could be drawn for sample standard deviations (σ) and for sample values of fraction defective, (p), in which case

Limits for sample standard deviations (σ) =

$$c_2\sigma' \pm 3\frac{\sigma'}{\sqrt{2n}}$$

where c_2 is a constant dependent on sample size:

$c_2 = 0.798$ for $n = 4$
$= 0.970$ for $n = 25$
$= 1.0$ for all practical purposes for n greater than 25

Limits for sample fraction defective (p) =

$$p' \pm 3\sqrt{\frac{p'(1-p')}{n}}$$

This gives a rather general law of sampling, namely, that the variation of sample value of $\bar{X}$, σ, and p is inversely proportional to the square root of the sample size, n.

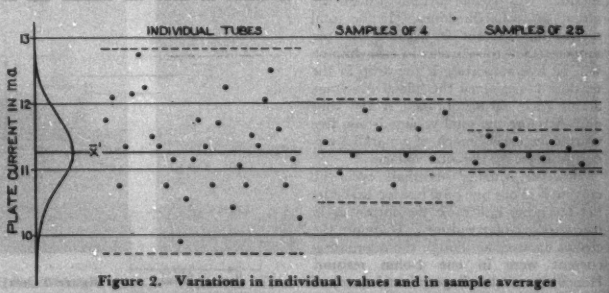

Figure 2. Variations in individual values and in sample averages

One of a series of articles prepared in the AIEE subcommittee on educational activities and sponsored by the AIEE subcommittee on statistical methods.

Personnel of the AIEE subcommittee on educational activities: J. Manuele, H. F. Dodge, A. I. Peterson, and R. E. Wareham.

All of this represents ideal conditions. It assumes a controlled process, but, at the same time, it does provide a basis that is useful in setting up criteria in reference to the following:

1. For judging the degree of control or stability of a process.

2. For controlling the process through frequent periodic samplings.

The dotted lines shown in Figure 2 are similar to control limits of control charts that are to be discussed in subsequent articles. They are limits within which "practically all" of the plotted points should fall when everything is running all right. Accordingly, when the plotted point for a sample falls outside the dotted lines, this may be taken as an indication of a findable cause of a change in process and can be used as a criterion for some action such, for example, as stopping the machine when the control chart is being used for process control.

REFERENCES

1. Applied General Statistics (book), Croxton, Cowden. Prentice-Hall Inc., New York, N. Y., 1942, chapters XII and XIII.

2. Supplement B, American Society for Testing Materials Manual on Presentation of Data, American Society for Testing Materials, 1943, Philadelphia, Pa. (reproduced as Appendix to ASA War Standard Z-1.2-1941 Control Chart Method of Analyzing Data, American Standards Association, New York, N. Y.).

Electrical Essays for Recreation

The following essays are presented for the recreation of the reader. The author's challenge to the reader is: Can you find the error in the reasoning accompanying the various examples?

MOTOR WITH NO FRAME REACTIONS

Figure 1 shows a bar magnet with a wire placed perpendicular to the magnet and a distance from the *N* pole. If the wire carries a current *i* in the direction indicated by the arrow there will be a force on the wire out of the page. The reaction on the *N* pole will be into the page. These forces produce a couple and if the wire is bent as shown and placed in bearings the U-shaped wire will tend to turn toward the reader and the magnet will tend to move away from the reader. Therefore if the magnet is fastened to the wire, say by some plastic material, the combination will rotate and supply a load.

An application for this type of motor would be the driving motor for a torpedo. The torpedo then could be fitted with only one propeller with no tendency for the propeller to remain stationary and let the torpedo rotate.

PARALLEL CIRCUIT PARADOX

Consider the circuit of Figure 2. A one-ohm resistance is connected in series with a rectifier. A similar circuit is connected in parallel with the first so that the rectifiers will permit current through the circuit in both directions. If the total alternating current is adjusted to ten amperes then the current in each branch will be five amperes. If the drop in the rectifier is neglected the effective voltage across each parallel branch is five volts and therefore the total voltage is also five volts since each branch of a parallel circuit is subject to the total voltage.

However, during one half cycle the current is in one one-ohm resistor, and during the other half cycle the current is in the other one-ohm resistor. Therefore the circuit behaves as though the alternating current were in one 1-ohm resistor. Hence the total voltage is ten instead of the five obtained in the foregoing discussion.

A PERPETUAL-MOTION MACHINE

This machine depends for its action on what is known as *retarded potentials*. The idea may be illustrated in connection with the stars. The star Arcturus is 40 light years away. It is so far away that it takes 40 years for the light emitted by it to reach us. When we look at it we do not see it where it is now but where it was 40 years ago! Light waves and electric-field and magnetic-field disturbances are propagated with the same finite velocity, about 186,000 miles per second.

Consider a positive charge q and a negative charge $-q$ placed r meters apart, Figure 3a. The attraction of one to the other is given by the formula

$$F = \frac{q^2}{kr^2} \qquad (1)$$

where F is in newtons, q in coulombs, r in meters, and k is the dielectric constant of the medium in meter-kilogram-second units.

Now suppose the negative charge is moving downward as indicated in Figure 3b. The negative charge is attracted to the positive charge by the force

$$F = \frac{q^2}{kr^2} \qquad (2)$$

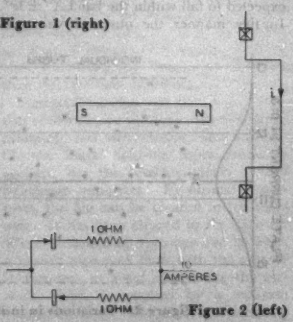

Figure 1 (right)

Figure 2 (left)

exerted to the left. The positive charge is attracted by the force

$$F' = \frac{q^2}{kR^2} \qquad (3)$$

directed to the point where the negative

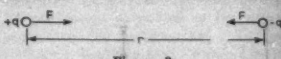

Figure 3a

Figure 3b

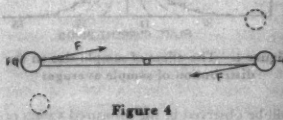

Figure 4

charge was an instant before, just as we see Arcturus where it was 40 years ago.

Now for the machine itself. Figure 4 shows the construction. It consists of two insulated electrodes placed at the ends of a bar that is pivoted at its middle. A charge is placed on each electrode, one positive, the other negative. The bar is rotated about the pivot. When the speed of rotation has been increased sufficiently the positive charge will be attracted toward the point where the negative charge was an instant before as shown by the arrow marked F in Figure 4. Similarly the negative charge is attracted toward the point where the positive charge was an instant before. The two forces shown in Figure 4 produce a couple in the direction of rotation and will overcome the friction of the pivot and enable us to obtain power from the shaft.

HARRY SOHON (A'28, M'34)

(Advanced-development engineer, Radio Corporation of America, Camden, N. J.)

25th Anniversary of Radiobroadcasting

History and events that led to the first scheduled broadcast of November 2, 1920, from the first established station, KDKA, Pittsburgh, with some interesting side lights, are discussed in this article on these two silver anniversaries.

"WILL ANYONE hearing this broadcast communicate with us, as we are anxious to know how far the broadcast is reaching and how it is being received." These words repeatedly came out of the air on the night of November 2, 1920—election night—interrupting the first scheduled broadcast made from the first established radio station, KDKA, Pittsburgh, Pa.

The chronology of events in the radio field since that fateful night reveals such wonderful achievements that it is difficult to believe that today's billion-dollar-a-year industry with a radio set for every two people in the United States, had its humble beginnings in an improvised shack atop one of the buildings of the then Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. The station could boast of no studio but had one room accommodating the transmitting equipment, a turntable for records, and a small staff of announcer, engineer, operator, and telephone-line handler.

Broadcasting began at six o'clock on that November night and continued until noon the following day, even though the election returns had been given as final the previous night when Candidate Cox had acknowledged defeat and conceded victory to Senator Harding. Throughout that stormy night, while the usual crowds stood before outdoor bulletin boards to see the returns, others were hearing the same returns in the comfort of their homes with crystal sets and earphones. In between announcement of returns music occasionally was injected.

The broadcast was a national sensation, acclaimed by newspapers all over the country. People telephoned for more news and less music. One report came from H. W. Irving, now transmitter supervisor at KDKA. Working as a Merchant Marine radio operator assigned to the United States Army transport, *Antigone*, he heard the program off the Virginia coast while en route with troops from Puerto Rico to New York.

But none of the comments sent in envisaged the future possibilities of this discovery nor could any seer of the 20's in his wildest flights of imagination have prophesied the developments that followed that broadcast, such as the extension of operation to higher and higher frequencies, the electronic television pickup or the development of the thermionic vacuum tube which eliminated the need of batteries and made possible operation of radio receivers from ordinary house current.

The construction of KDKA, begun only one month prior to the election, was entrusted to the late Frank Conrad (A '02, F '37) then assistant chief engineer of the Westinghouse Company and an enthusiastic radio amateur. The first KDKA license was issued October 27, 1920, and call letters were assigned from a roster maintained to provide identification for ships and shore stations, these being the only regular radio services then in operation under formal license by the Federal Government. Assisting Doctor Conrad in his work was his long-time friend and coworker, D. G. Little, former Kalamazoo, Mich., radio "ham" and at present consulting engineer in the Westinghouse industrial electronics division at Baltimore, Md. Mr. Little had been tinkering with vacuum-tube radio since 1910.

The story goes that Frank Conrad first had become interested in radio in 1915 when to settle a $5 bet on the accuracy of his $12 watch he had built a small wireless receiver to hear time signals from the Naval transmitter at Arlington, Va. Intrigued by his new hobby Doctor Conrad turned next to the construction of a transmitter which he installed on the second floor of a garage at the rear of his residence in Wilkinsburg, Pa. First official record of this station appeared in the August 1, 1916, edition of the *Radio Service Bulletin* issued monthly by the Bureau of Navigation of the United States Department of Commerce. Shortly thereafter security precautions, necessitated by the entry of the United States into World War I, brought about the cancellation of his station licensed as 8XK along with all amateur licenses. However, the ban was lifted in October 1919, and on October 17 of that year Doctor Conrad delighted "hams" with a phonograph-record concert. He had been bored with the monotony of radio messages discussing the kind of equipment being used, and began to substitute music for voice. The music delighted and amazed amateurs who became convinced that music really could be transmitted through space. So heavy was the demand for "more" that Doctor Conrad was forced to announce that, instead of complying with each individual request, he would "broadcast" records for two hours each Wednesday and Saturday evening. This is said to be the first recorded use of the word "broadcast" to describe a radio service. These broadcasts soon exhausted Doctor Conrad's supply of records and the Hamilton Music Store in Wilkinsburg offered a continuing supply of records if he would announce that the records could be purchased at that store. Thus sprang up the first radio advertiser.

Meanwhile interest in these broadcasts was becoming so widespread that a station

Figure 1. First broadcasting studio (1921) was in a tent

Figure 2. Transmitter used by Doctor Conrad in 1918

Figure 3. Early Westinghouse crystal-detector set

Figure 4. First real studio at KDKA installed in 1922

was authorized and a license application submitted October 16, 1920, and election night—only a little more than two weeks away—selected for the grand opening.

For the first six months of its existence KDKA was a radio station without a studio. There had been little need for one, since all programs were originated either as phonograph records played on turntables in the tiny transmitter penthouse atop the East Pittsburgh plant, or from churches, theaters, hotels, or other remote points. However, in May 1921, it was decided that the program structure should include live band and orchestral talent as well as recordings, and the services of several musical organizations of Westinghouse employees were secured. First programs were broadcast from an auditorium at the plant, but room resonance was so great that engineers immediately set about finding other facilities—a tent on a roof next to the transmitter penthouse was succeeded by an indoor studio at East Pittsburgh.

Many of those connected with the pioneer efforts of KDKA tell about the "growing pains" of the station in those early days of broadcasting. Some recall the whistle of a passing freight train which in the days of the tent studio became a regular feature at each evening's broadcast; others refer to the first Roger Babson's broadcast when it was discovered at the end that the transmitter had not been operating; and still others tell of the occasion when the angry words of a tenor not in good radio taste were summarily taken off the air.

These occurrences appear puerile in the light of the finished broadcasts of later days such as regular broadcasts of church services, important sports activities, market reports, news events, and subsequently all history-making events.

With broadcasting well on its way late in 1920 Doctor Conrad again concentrated on his amateur station at Wilkinsburg. Like all amateurs, his 8XK operated in the short-wave band as these stations were not rated of sufficient importance to warrant places in the highly regarded standard band. The short-wave band, on the other hand, was considered of little value, but Doctor Conrad did not share this sentiment. With considerable doubt in his mind about the generally accepted theories that the range of short waves definitely was limited Doctor Conrad began experiments in the spring of 1921. Tests revealed that short waves, reflected by the Heaviside layer and other ionized strata of the earth's rarified outer atmosphere, bounce back and forth between these layers and the earth and can be received only in those places where they strike the earth's surface. Shortly after and as a result of these researches the short-wave band became the most useful in the electromagnetic spectrum.

Another contribution to radio was Vladimir Zworykin's (M '22, F '45) demonstration of an electronic-beam television pickup which led to the iconoscope and "kinescope"—standard television equipment today.

The chronology of radiobroadcasting includes many interesting data and tells the story of many zealous experimenters and pioneers, some of whom are not living in the year 1945 to note the two silver anniversaries—one commemorating the world's first scheduled broadcast, November 2, 1920; the other marking establishment of KDKA, Pittsburgh, pioneer Westinghouse radio station from which that historic broadcast was made. Yet because of them—those living and those departed—who contributed no small part to the development of radio, cultural, educational, social, and amusement programs are being broadcast for the information and delectation of listeners scattered about the world. Its benefits in World War II can be stated best by the serviceman who "tuned" in on home programs, and in spirit, at least, joined the folks he left behind in an evening at the radio.

Communications in Italy

Communications networks in Italy have been restored so effectively by the United States Army Signal Corps that all sections of the country now are linked together by adequate cable and wire facilities for military and occupational purposes, according to a report to the Chief Signal Officer from the Mediterranean Theater. The prewar Italian civilian wire-communications network was both extensive and diversified but, as the result of German destruction, rehabilitation was required on both inside and outside plants before much of that system could be employed. Combining Italian and American equipment into an efficient and reliable network presented many technical problems.

In many areas military requirements were of such a nature and extent that existing civilian facilities were not adequate from either the standpoint of territory covered or the number and types of circuits available. Consequently, in addition to rehabilitation of the civilian system, the Signal Corps was required to construct local and long-line facilities for exclusive military use. This objective was accomplished by the addition of open-wire circuits on reconstructed civilian routes and the construction of strictly military open wire and cable routes.

Due to the swiftness of the Allied breakthrough in Northern Italy, much of the Italian civilian system and the German military network in those areas was captured before great destruction had been wrought through either battle damage or deliberate German demolition. Consequently, through the utilization of skilled German prisoners of war, supervised by Allied communication personnel, much of the network in Northern Italy was made available with a minimum of rehabilitation and new construction. Some German installations now are operated by German personnel under Allied supervision.

INSTITUTE ACTIVITIES

AIEE Officers to Be Nominated for 1946 Election

For the nomination of officers to be voted upon in the spring of 1946, the AIEE nominating committee will meet in New York, N. Y., in January 1946. The officers to be elected are: a president, a treasurer, three directors, and five vice-presidents, one from each of the odd-numbered geographical Districts. Fellows only are eligible for the office of president, and Members and Fellows for the offices of vice-president, director, and treasurer.

To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee, all such suggestions must be received by the secretary of the committee at Institute headquarters, not later than December 15, 1945.

In accordance with the provisions in the constitution and bylaws, as amended during 1935 and quoted in the following paragraphs, actions relating to the organization of the nominating committee are now under way.

Constitution

28. There shall be constituted each year a nominating committee consisting of one representative of each geographical District, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical Districts; all to be selected when and as provided in the bylaws. The secretary of the Institute shall be the secretary of the nominating committee, without voting power.

29. The executive committee of each geographical District shall act as a nominating committee of the candidate for election as vice-president of that District, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The nominating committee shall name on or before January 31 of each year, one or more candidates for president, treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice-presidents as have been named by the nominating committees of the respective geographical Districts, if received by the nominating committee when and as provided in the bylaws; otherwise the nominating committee shall nominate one or more candidates for vice-president(s) from the District(s) concerned.

Bylaws

Sec. 22. During September of each year, the secretary of the nominating committee shall notify the chairman of the executive committee of each geographical District that by December 15 of that year the executive committee of each district must select a member of that District to serve as a member of the nominating committee, and shall by December 15, notify the secretary of the nominating committee of the name of the member selected.

During September of each year, the secretary of the nominating committee shall notify the chairman of the executive committee of each geographical District in which there is or will be during the year a vacancy in the office of vice-president, that by December 15 of that year a nomination for a vice-president from that District, made by the District executive committee, must be in the hands of the secretary of the nominating committee.

Between October 1 and December 15 of each year, the board of directors shall choose 5 of its members to serve on the nominating committee and shall notify the secretary of that committee of the names so selected and shall also notify the 5 members selected.

The secretary of the nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than January 31. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the nominating committee must be received by the secretary of the committee by December 15. The nominations as made by the nominating committee shall be published in the March issue of *Electrical Engineering* (Journal of AIEE), or otherwise mailed to the Institute membership not later than the first week in March.

INDEPENDENT NOMINATIONS

Independent nominations may be made in accordance with provisions in article VI, section 31, of the constitution and section 23 of the bylaws, which are quoted below:

Constitution

31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the secretary when and as provided in the bylaws; such petitions for the nomination of vice-presidents shall be signed only by members within the District concerned.

Bylaws

Sec. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with article VI, section 31 (constitution), must be received by the secretary of the nominating committee not later than March 25 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the nominating committee in accordance with article VI of the constitution and sent by the secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(*Signed*) H. H. Henline,
Secretary

October 1, 1945

ABSTRACTS

The following abstracts of technical papers included in the fall program are in addition to those published in the September issue of *Electrical Engineering*, pages 330–33.

Statistical-Methods Applications

45-142—Statistical Methods in the Development of Apparatus Life Quality; *E. N. Ferrell*. *20 cents*. Life tests on a new design of relay were so planned that the methods of statistical quality control could be used to separate assignable causes for variation from random causes for variation during life. The relays were inspected frequently at the beginning of the test and less frequently later. The results of these inspections were plotted in the form of control charts. From a study of points outside control limits, improvements were made in the design, the method of manufacture, and the method of test. From a study of the control limits and the number of points within them predictions were made as to the useful life to be expected. Simplified methods used in recording and analyzing the data and in establishing trends are described.

45-167—The Direct- and Quadrature-Axis Equivalent Circuits of the Synchronous Machine; *A. W. Rankin* (*A '38*). *30 cents*. The equivalent circuits of the synchronous machine are needed for the determination of the subtransient reactances; of damping and synchronizing torques; the design of damper windings, and for many other problems of a design or operating nature. This paper presents more complete and more exact direct- and quadrature-axis equivalent circuits than have heretofore been available. Formulas for all the per-unit impedances needed by the equivalent circuits are derived and presented in this paper. These per-unit impedances are derived in a direct systematized form which eliminates the possibility of errors caused by inadvertent change of the base rotor currents. The permeance coefficients needed by the reactance formulas are determined by means of a gap reluctance expression whose accuracy is proved by comparison with similar coefficients evaluated from flux plots. Numerical values of these permeance coefficients are presented for a typical pole configuration.

Power Generation

45-168—Modern Practice in Power-Plant Auxiliary Equipment and Systems; *H. N. Muller, Jr.* (*M '43*). *15 cents*. This paper hits high spots in the field of central-station auxiliary practice. Subjects are selected to include instances in which the design engineer may exercise judgment in choosing alternate items of apparatus, or in which specifications may influence apparatus design by emphasis on particular requirements. The paper includes discussions on several salient factors influencing motor design, a brief summary on present-day practice in the use of air circuit breakers and metal-clad switchgear, and a description of trends in power-distribution systems for central-station auxiliaries. Of interest is an analysis of the applicability of the secondary network system to auxiliary supply. A number of points that the design engineer should keep in mind when choosing the distribution system for power-plant auxiliaries are listed and discussed. The different forms that an auxiliary-system network may take are discussed with the object in mind of showing the extreme flexibility obtainable when this method of power supply to auxiliaries is adopted.

STANDARDS

Test Code for Synchronous Machines. A formally approved edition of the "Test Code for Synchronous Machines" now is available. This test code, issued in preliminary form in 1937, has been revised completely by the subcommittee on synchronous machines of the AIEE committee on electric

machinery. It was approved in its final form by the board of directors on February 27, 1945. The code contains instructions for conducting the more generally applicable and acceptable tests to determine the performance characteristics of synchronous machines. It includes performance tests for synchronous generators, synchronous motors (larger than fractional horsepower), synchronous condensers, frequency changers, and rotary phase advancers. Copies of the code, number 503, may be obtained from AIEE headquarters, 33 West 39th Street, New York 18, N. Y., at a cost of 30 cents each, with the usual 50-per-cent discount to AIEE members on single copies.

Condensing Steam Turbine-Generators. A joint committee of AIEE and American Society of Mechanical Engineers on steam turbine-generators has developed preferred Standards and Standards specification data for large 3,600-rpm three-phase 60-cycle condensing steam turbine-generators (larger than 10,000-kw rated capacity). The joint committee prepared the preferred Standards and these have been approved formally by both the AIEE and the ASME. The Standards specification data for generators was prepared by the AIEE group of the joint committee and approved by the AIEE board of directors on February 27, 1945. The Standards and the specification data cover both air-cooled and hydrogen-cooled units. Copies of the pamphlet, numbers 601 and 602 containing both the Standards and the specifications, may be obtained from AIEE headquarters, 33 West 39th Street, New York 18, N. Y., at a cost of 60 cents each, with the usual 50-per-cent discount to AIEE members on single copies.

AIEE Standard No. 45A Withdrawn. AIEE pamphlet 45A, a modification of and supplement to AIEE Standard 45, "Recommended Practice for Electrical Installations on Shipboard," as issued in revised form January 1, 1944, and to apply during the "national emergency" only, has been withdrawn as obsolete by authorization of the AIEE committee on marine transportation. This action is based on the fact that the restrictions laid down by the War Production Board, which necessitated the issuance of 45A have been removed and, in addition, all vessels now being constructed are not limited for use during the national emergency. A new edition of pamphlet 45, including all items covered in 45A which it has been agreed should be recommended as standard construction, is now in course of publication. It should be available in late October.

A-C Power Circuit Breakers. By action of the American Standards Association as of May 16, 1945, an approved American Standard for "A-C Power Circuit Breakers" just has been made available in pamphlet form. This Standard, C37.4 to C37.9, originally was published in proposed form in January 1941 for trial use and study. On the basis of suggestions received during the trial period, principally from the protective devices committee of AIEE, the proposed Standards were brought to their present approved form. C37.4 to 9 supersedes AIEE publication 19, "A-C Power Circuit Breakers" issued in 1943 to provide for an interim standard. The new American Standard contains in the one pamphlet six sections as follows: "A-C Power Circuit Breakers," C37.4; "Methods for Determining the Rms Value of a Sinusoidal Current Wave and a Normal Frequency Recovery Voltage," C37.5; "Schedule of Preferred Ratings for Power-Circuit Breakers," C37.6; "Operating Duty for Standard and Reclosing Service," C37.7; "Rated Control Voltages," C37.8; and "Test Code for Power Circuit Breakers," C37.9. Copies can be obtained from AIEE headquarters, 33 West 39th Street, New York 18, N. Y. at $1.25 net (no discount to members).

SECTION

Montreal Electronics Group

As a result of a questionnaire and an indicated request for such activity, a technical group for the discussion and study of industrial electronic equipment has been initiated by the Montreal Section.

Two meetings have been held at which an agreement was reached on submitting a program for consideration. Discussions will include the following:

(a). Some atomic theory pertinent to industrial electronics.

(b). High-vacuum-tube construction and characteristics (with reference to atomic theories).

(c). High-vacuum-tube applications.

(d). High-vacuum-tube applications.

(e). Low-vacuum-tube construction and characteristics.

(f). Low-vacuum-tube applications.

(g). Rectifier transformers.

(h). Light-sensitive devices.

(i). High frequencies.

New York Lecture Courses

Autumn lecture courses are being resumed by the New York Section, AIEE. One feature of the curriculum is planned for engineers who want review of supplemental engineering training, and those preparing for professional license examination in New York and in New Jersey. The subjects covered are "motors," "radar," "induction and dielectric heating," and a symposium will be held on "servomechanisms."

PERSONAL

William Percy Dobson (A '13, M '19, F '43) director of research, and head of the research and testing department, Hydro-Electric Power Commission of Canada, Toronto, Ontario, has been appointed 1945–46 chairman of the AIEE Standards committee of which he has been vice-chairman for the past year. He was born near Georgetown, Ontario, Canada, and was graduated from the University of Toronto in 1911 with a degree in electrical engineering. He joined the Toronto Hydro-Electric System after graduation and remained until 1912 when he was awarded a research fellowship by the engineering alumni association of the University of Toronto.

W. P. Dobson

He spent 18 months investigating transient electrical phenomena on the high-voltage power systems of the Hydro-Electric Power Commission of Ontario and the Toronto Power Company. In 1914 he joined the Hydro-Electric Power Commision as laboratory engineer. During the period when the commission's systems were expanding rapidly he was active in high-voltage transmission studies, and in the investigation of lightning phenomena, grounding, and protection of systems. He has been active in engineering standardization for more than 25 years, serving as member of the Standards committee of the AIEE for the past seven years. He was also vice-president of the AIEE Canada District for 1926–27. He is chairman of the Canadian Standards Association's committee on the Canadian electrical code. In 1919 he organized the approvals laboratory of the Hydro-Electric Power Commision for the testing and certification of electric materials and equipment for fire and accident hazards. Later the Canadian Standards Association assumed responsibility for this work on a national scale, and Mr. Dobson now acts as chairman of the approvals division. Mr. Dobson also serves on technical committees of the National Research Council of Canada, and the American Society for Testing Materials. He is also identified with the Ontario Association of Profesional Engineers; Dominion Council of Profesional Engineers; Engineering Institute of Canada: and was representative of the Dominion Council in the 1944 negotiations between the Dominion Government and the engineering and allied profesions.

Dressel DeWitt Ewing (A '11, F '21) head of the school of electrical engineering, Purdue University, Lafayette, Ind., has been ap-

D. D. Ewing

pointed 1945–46 chairman of the AIEE committee on code of principles of professional conduct of which he has been a member since 1942. Professor Ewing was born in Vanlue, Ohio, and was graduated with a degree in electrical and mechanical engineering at Ohio Northern University in 1906. His first engineering work was as a cable testman with the Central Printing Telegraph and Telephone Company, Pittsburgh, Pa. Shortly thereafter he joined the engineering staff of Missouri Pacific Railway, St. Louis, Mo. In the autumn of 1907 he returned to Ohio Northern University as an instructor in electrical and mechanical engineering. In 1912 he became a graduate student and an assistant in electrical engineering at Purdue University. A year later he was appointed assistant professor of electric-railway engineering there and in various capacities has continued to serve the university since that time. In his early years as a teacher, Professor Ewing spent several summers with Westinghouse Electric and Manufacturing Company on railway electrification projects. Subsequently, he worked as a consultant on rate cases. Professor Ewing has acted as a director of research on projects for railway associations and manufacturing companies, and is the author of many articles on electric-railway and power problems. For many years he has served as a member of the power-transmission and distribution committee and of the way committee of the American Electric Railway Association, now the American Transit Association. He has served in various offices of the AIEE Central Indiana Section and has worked on the following committees: joint committee on welded rail joints, 1925–1933; electric welding, 1932–44; power transmission and distribution, 1936–42; and transportation (land transportation) 1936–42.

Morris Daniel Hooven (A '24, M '30, F '44) electrical engineer, electrical engineering department, Public Service Electric and Gas Company, Newark, N. J., has been appointed 1945–46 chairman of the AIEE technical-program committee of which he has been a member since 1942, and of the committee on award of Institute prizes. Mr. Hooven was born in Weatherly, Pa., May 30, 1897, and following studies at the Carnegie Institute of Technology, University of Vermont, and the Sheffield Scientific School, Yale University, was graduated from Bucknell University in 1920 with the degree of bachelor of science. In 1913 he was employed at Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and intermittently from 1914 to 1920 served as analyst and furnace chemist with the Carnegie Steel Company, Braddock, Pa. In World War I Mr. Hooven was in the United States Army Signal Corps. In 1920 he returned to the Westinghouse Company and a year later became manager of the radio department of the Robbins Electric Company, Pittsburgh, Pa. He entered the employ of Public Service Electric Company, Newark, N. J., in 1922 as one of the group engaged in the planning and design of the 132-kv system. He handled miscellaneous assignments in transmission and substation work receiving the title of assistant transmission and substation engineer, electrical-distribution department, in 1939. Since 1942 he has been electrical engineer, electrical-engineering department. Mr. Hooven has been active in the work of the New York Section and served as chairman in 1944–45. He has served on other industrial and professional bodies including Edison Electric Institute; Institute of Radio Engineers; Montclair Society of Engineers; and the American Standards Association.

Robert Ernest Doherty (A '16, M '27, F '39) president, Carnegie Institute of Technology, Pittsburgh, Pa., has been appointed chairman of the AIEE Edison Medal committee for 1945–46. Born January 22, 1885, in Clay City, Ill., Doctor Doherty received the degree of bachelor of science from the University of Illinois in 1909, that of master of science from Union College in 1920, and the honorary degrees of master of arts, 1931, Yale University, and doctor of laws from Tufts College and the University of Pittsburgh, 1936. He was employed as a student engineer by the General Electric Company, Schenectady, N. Y., in 1909, becoming a designing engineer in 1910 and a consulting engineer in 1923. In 1931 Doctor Doherty was appointed professor of electrical engineering at Yale University, New Haven, Conn., and in 1933 became dean of the school of engineering. He has been president of the Carnegie Institute since 1936. He has been active on various committees including the consultative committee on engineering, War Manpower Commission, 1942–43; and the advisory committee, Civil Advisory Council of the Office of Chief of Ordnance. In 1937 Doctor Doherty was the recipient of the Lamme Medal. He is a past-president of the Society for the Promotion of Engineering Education and a former chairman of the Engineers' Council for Professional Development.

Charles Frederick Wagner (A '20, M '27, F '40) manager, central-station engineering department, Westinghouse Electric Corporation, East Pittsburgh, Pa., has been appointed chairman of the AIEE publication committee for 1945–46. Born in Pittsburgh, Pa., on March 20, 1895, Mr. Wagner was graduated from the Carnegie Institute of Technology in 1917 with a bachelor-of-science degree. His entire professional career has been with the Westinghouse Company which he joined in 1918 after a year of graduate study at the University of Chicago. During this time his work has included research and development of mercury-arc rectifiers and inverter systems; the study of transmission-system stability and short-circuit transients; and the analysis of machine performance and high-voltage lightning phenomena. In 1938 he was appointed consulting transmission engineer, and in 1941 manager of the central-station engineering department. Mr. Wagner is chairman of the general-systems subcommittee of the AIEE power-transmission and distribution committee of which he is a member, and is a member of the planning and co-ordination committee, and the transformer subcommittee of the electric-machinery committee. In 1938 he was awarded the best-paper prize in engineering practice and in 1943 the best-paper prize in theory and research as co-author of "Shielding of Substations."

Alexander Maxwell (A '03, M '12, F '37) director of engineering, Edison Electric Institute, New York, N. Y., has been appointed chairman of the AIEE board of examiners for 1945–46. He has been a member of the board since 1938. Mr. Maxwell was born in New York, N. Y., in 1878. In 1894 he became an assistant in the laboratory and testing department of the Westinghouse Electric and Manufacturing Company, Newark, N. J., and from 1895 to 1924 he was associated with the former New York (N. Y.) Edison Company and predecessor electric lighting companies as assistant superintendent of operation, in charge of the electrical and general laboratory and as engineer of distribution. Mr. Maxwell became an engineer for the National Electric Light Association, New York, in 1924 and continued with that organization until it was dissolved and succeeded by the Edison Electric Institute. He was made director of engineering for the latter company upon its formation in 1933. This position includes supervision of the organized activities of the electric-light and power-supply industry in the fields of engi-

M. D. Hooven

R. E. Doherty

C. F. Wagner

Alexander Maxwell

neering and operating and allied managerial activities. Mr. Maxwell is a member of the AIEE Standards committee and was first chairman of the domestic- and commercial-applications committee.

Robert Joseph Wiseman (A '16, M '20, F '27) chief engineer, The Okonite Company, Passaic, N. J., and Okonite-Callender Cable Company, has been appointed 1945–46 chairman of the AIEE committee on power transmission and distribution. Doctor Wiseman, born in July 1890 at Cambridge, Mass., was graduated from the Massachusetts Institute of Technology in 1912 with the degree of bachelor of science in electrical engineering. In 1915 he received the doctor-of-science degree from the same university. From 1915 until 1917 he was a member of the research staff of the Massachusetts Institute of Technology, Cambridge, and in the latter year accepted a position in the engineering department of the Western Union Telegraph Company, New York, N. Y. From 1918 until 1921 he served the National Conduit and Cable Company as wire and cable engineer. Then in 1921 he became research engineer of The Okonite Company. Seven years later he was made chief engineer. Also from 1924 to 1928 he served as research engineer of the Okonite-Callender Cable Company becoming chief engineer in 1928. Doctor Wiseman has been a member of several AIEE committees—research, 1931–39; instruments and measurements, 1937–39; application to marine work and marine transportation, 1937–43; board of examiners 1939–45; and power transmission and distribution, 1939–45. He is an associate member, Institution of Electrical Engineers of England; member, American Society for Testing Materials; member, committee on insulation of National Research Council; member, advisory committee on transmission and distribution, Edison Electric Institute; member, American Institute of Mining and Metallurgical Engineers; member Electrochemical Society; and past-president and secretary of Insulated Power Cable Engineers Association. He also has written papers on electrical insulation for electric-power cables.

Walter R. G. Baker (A '19, M '41) vice-president in charge of the electronics department, General Electric Company, Bridgeport, Conn., has been appointed 1945–46 chairman of the AIEE committee on electronics. Mr. Baker was born in Lockport, N. Y., on November 30, 1891, and was graduated from Union College from which he holds three degrees including the honorary degree of doctor of science. He joined the research laboratories of the General Electric Company, Schenectady, N. Y., in 1917, and worked on vacuum-tube transmitters and receivers. As the work increased a separate radio department was established, and he was made designing engineer in charge of transmitters. In 1924 his responsibility was further enlarged to include the design of all radio products, and two years later he was given complete charge of development, design, and production. Under his supervision some of the broadcast transmitters of the company were designed, and the South Schenectady developmental laboratory was designed and built. On the formation of the Radio Corporation of America and Victor Corporation in 1929, Doctor Baker went to Camden, N. J., to head the radio-engineering activities of the new organization. Within the year he was placed in charge of production, and later became general manager of the plant. In 1935 the General Electric Company transferred its radio-receiver activities to Bridgeport, and there Doctor Baker resumed his connections with the company, being named managing engineer in 1936, a post he held until May 1939 when he was elevated to the position of manager of the radio and television department. In 1941 he was presented a gold escutcheon plaque by the Institute of Radio Engineers in recognition of his work as chairman of the national television systems committee. He is a member of the National Electrical Manufacturers' Association, chairman of the Radio Technical Planning Board, fellow of the Institute of Radio Engineers, and director of the engineering department, Radio Manufacturers Association.

Raymond T. Henry (A '24, M '29, F '33) chief electrical engineer, engineering department, Buffalo (N. Y.) Niagara and Eastern Power Company, has been appointed chairman of the AIEE committee on the Charles LeGeyt Fortescue Fellowship for 1945–47. For further biographical details see *Electrical Engineering*, March 1944, page 110.

James Ferdinand Fairman (A '20, M '27, F '35) assistant vice-president, Consolidated Edison Company of New York (N. Y.), Inc., has been appointed chairman of the AIEE committee on planning and co-ordination. He has also served on the executive committee, 1944-45 and finance committee, 1944-45. For further biographical details see *Electrical Engineering*, March 1944, page 110.

Mark Eldredge (A '14, F '33) formerly chief, military and industrial unit, power division, Office of War Utilities, War Production Board, Washington, D. C., is now chief, electrical equipment section, Office of Surplus Property, Reconstruction Finance Corporation, Washington. Mr. Eldredge was born in Woodbury, N. J., and was graduated from Worcester Polytechnic Institute in 1906. He has been associated with many concerns, including General Electric Company, Schenectady, N. Y., United States Reclamation Service, Williston, N. Dak., and the Gilson Asphaltum Company, Dragon, Utah. From 1911 to 1913 he was professor of electrical engineering in Ewing College, Allahabad, India. During World War I he was commissioned a captain in the Quartermaster Corps of the United States Army. He returned to India in 1919 and was employed by the Ludlow Jute Company. In 1924 he became chief engineer for the Memphis (Tenn.) Power and Light Company. When the company was purchased by the City of Memphis in 1939, he became director, electric division, Memphis Light, Gas and Water Department. In 1940 Mr. Eldredge began devoting his energies to various war agencies. He has been active in AIEE affairs, and has served on many committees including the constitution and bylaws, of which he has been a member since 1941 and chairman since 1944, and planning and co-ordination committee, 1944–45. He was a vice-president 1935–37, and a director 1939–43.

Harry Sohon (A '28, M '43) formerly assistant professor of electrical engineering, Moore school of electrical engineering, University of Pennsylvania, Philadelphia, has been appointed advanced-development engineer with the Radio Corporation of America, Camden, N. J. He was born in New York, N. Y., and was graduated from Cornell University as electrical engineer in 1926, receiving the degrees of master of electrical engineering in 1930 and doctor of philosophy in 1932. Early in his career he served for a short period in the test department of General Electric Company, Schenectady, N. Y., and in 1930 he became instructor in electrical engineering at Cornell University, Ithaca, N. Y. After his appointment as assistant professor of electrical engineering there, and followed by a short period in the same capacity at the University of Connecticut, Storrs, Doctor Sohon accepted the position of assistant professor of electrical engineering at the University of Pennsylvania. He is the author of "Engineering Mathematics," and prepared the electrical essays recently published. (*EE, Aug.'45, p. 294; Oct.'45, p. 364.*)

R. J. Wiseman

R. T. Henry

J. F. Fairman

W. R. G. Baker

L. H. Hill (A '22, F '38) formerly vice-president in charge of industrial relations, Allis-Chalmers Manufacturing Company, Milwaukee, Wis., has resigned to become publisher of *Electrical World* and *Electrical Contracting*, published by McGraw-Hill Publishing Company, New York, N. Y. Mr. Hill was born in 1899 in Toms River, N. J., and was graduated from Cornell University with a degree in electrical engineering. From 1920 until 1922 he was an instructor in electrical engineering at the university, and in the latter year became design engineer, transformer-engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. In 1928 he was named manager, transformer division, American Brown Boveri Electric Corporation, Camden, N. J. He has been a member of the Allis-Chalmers organization since 1931 when the company took over the American Brown Boveri Company. Prior to becoming vice-president in charge of industrial relations, Mr. Hill was assistant manager of the electrical department. He holds approximately 40 patents on electric machinery and is the author of a text on transformers. Throughout World War II, Mr. Hill was active on the War Labor Board and was President Truman's first appointee as a full-industry member of the board. He is co-author of a recently published book "Management at the Bargaining Table."

B. K. Boulton (M '31) formerly superintendent of operation, Quebec Hydro-Power Commission, Beauharnois, Quebec, Canada, has been appointed president, Wartime Housing Limited. Mr. Boulton was born in Ottawa, Ontario, Canada, in 1903, and was graduated from McGill University with a degree of bachelor of science in electrical engineering in 1925. At first he was associated with the Quebec Development Company, working at one time as engineer in charge of construction of the transmission system for the Duke Price Power Company. In 1929 he joined the Beauharnois (Quebec) Construction Company and was put in charge of all electrical work in the construction and permanent electrical installation in the Beauharnois station. Mr. Boulton is a member of the Canadian Electrical Association, of which he is a past-chairman of the electrical equipment committee; the Engineering Institute of Canada; and the Corporation of Professional Engineers of Quebec.

Haraden Pratt (A '15, F '37) vice-president and chief engineer, Mackay Radio and Telegraph Company, Inc., New York, N. Y., has been elected vice-president and chief engineer of All-American Cable and Radio, Inc., and the Commercial Cable Company. He has also been elected chairman of the Radio Technical Planning Board. He received the bachelor-of-science degree in electrical engineering from the University of California, in 1914, and upon graduation became associated with the Marconi Wireless Telegraph Company of America, San Francisco, Calif. In 1915 Mr. Pratt became expert radio aid at the Mare Island (Calif.) Navy Yard, in 1918 he was associated with the bureau of steam engineering, Navy Department, Washington, D. C., and in 1920 left to become an engineer for the Federal Telegraph Company, Palo Alto, Calif. In 1927 he was named engineer in charge of the development of radio aids for air navigation for the Bureau of Standards, Department of Commerce, Washington, and a year later accepted the position of chief engineer of Mackay Radio and Telegraph Company, Inc. A past president of the Institute of Radio Engineers, in 1944 he was awarded a medal of honor for his work in the field of radio communications.

J. T. Barron (M '20, F '27) vice-president in charge of electric operation, Public Service Electric and Gas Company, Newark, N. J., has been elected a director of the Public Service Corporation of New Jersey. Mr. Barron was born in 1884 in Columbia, S. C., and was graduated from the University of South Carolina with the degree of bachelor of science in 1905. From that year until 1907 he was associated with the testing department of the General Electric Company, Schenectady N. Y. In 1907 he entered the service of the Public Service Electric and Gas Company, has been identified with the testing laboratory and the construction department, and has served as chief operator of the substations and generating stations in the central division and as superintendent of the central division. In 1926 he was made general manager of the electric department and and has been a vice-president of the company since 1935.

F. E. Harrell (A '26, F '40) formerly chief engineer, Reliance Electric and Engineering Company, Cleveland, Ohio, has been appointed general works manager of the company. Mr. Harrell joined the sales engineering department of the Reliance Company's Chicago (Ill.) office in 1924, after graduation from Purdue University. In 1927 he was transferred to general engineering in Cleveland, and in 1924 became assistant chief engineer. **W. R. Hough** (A '35, M '41) product development engineer, has been named chief engineer to succeed Mr. Harrell. Mr. Hough became associated with the company in 1929, following his graduation from the University of Michigan. Prior to his work on product development he served as junior engineer, chief draftsman, and a-c design engineer. Both Mr. Harrell and Mr. Hough are past chairmen of the AIEE Cleveland Section.

J. H. Lampe (A' 20, M '26) former dean of engineering of the University of Connecticut, Storrs, recently became dean of the school of engineering at the North Carolina State College, Raleigh. Doctor Lampe is a native of Baltimore, Md. He received the degrees of bachelor of science in 1918, master of electrical engineering in 1925, and doctor of engineering in 1931, all from Johns Hopkins University, Baltimore. After a period of service with the United States Army from 1918–19, he taught electrical engineering at Johns Hopkins University until 1938, when he became head of the department of electrical engineering at the University of Connecticut. He was promoted to dean of engineering there in 1940. His industrial connections have dealt with such problems as high-voltage cable investigations, electrolysis, magnetic tests, and electric-power generation and transmission.

H. A. Winne (A '16, F '45) vice-president in charge of engineering, General Electric Company, Schenectady, N. Y., has been appointed vice-president in charge of engineering policy for the entire company. Mr. Winne joined the General Electric Company as a student engineer in the testing department in 1910. After holding various positions he was elected vice-president in charge of apparatus-design engineering in 1941 and assumed the duties of manager of engineering in January 1945. **E. E. Johnson** (A '25, M '40) assistant engineer, aeronautics and marine-engineering division has been made engineering manager of the apparatus department to succeed Mr. Winne. Mr. Johnson has been with the General Electric Company since 1922.

C. L. Dawes (A '12, F '35) associate professor of electrical engineering, Harvard University, Cambridge, Mass., has been awarded the honorary degree of doctor of engineering by Northeastern University. Doctor Dawes was born in Somerville, Mass., and is a graduate of the Massachusetts Institute of Technology with the degree of bachelor of science in electrical engineering. There he served as assistant in electrical engineering from 1909–11, and from 1911–19 he was instructor at Harvard University and also at Massachusetts Institute of Technology. In 1919 he was appointed assistant professor of electrical engineering at Harvard University and in 1931 associate professor. Doctor Dawes is the author of many technical papers and books and has served on many AIEE committees.

H. F. Kingdon (A '26, M '38) works manager, Commonwealth Electric Corporation, Ltd., Welland, Ontario, Canada, has been appointed chief engineer and manager of the transformer department of the Eisler Engineering Company, Newark, N. J. Mr. Kingdon received his engineering degree from the University of Michigan in 1923. He entered the transformer engineering department of General Electric Company at Pittsfield, Mass., and in 1925 he was appointed chief transformer engineer of English Electric Company of Canada and assistant manager in 1929. Five years later he joined the Commonwealth Electric Corporation as chief transformer engineer and assistant manager and in 1937 he was made works manager.

C. A. Powel (M '20, F '41) junior past president AIEE, and manager, headquarters engineering departments of the Westinghouse Electric Corporation, East Pittsburgh, Pa., who is now on leave as chief of the electrical and radio branch of the Allied Control Commission, has received the Order of Merit from his company "for his unusual ability to recognize opportunities for the development and application of electrical equipment in the electrical power industry, for his skill in . . . executing plans to further them . . . and for his . . . promotion of broad engineering and educational activities on a national scale." The Order of Merit is the highest honor conferred on Westinghouse employees. Mr. Powel joined the company 26 years ago.

David Williams (A '23) lieutenant commander of the United States Naval Reserve, and on wartime leave as manager, electrical equipment purchases of the Consolidated Edison Company of New York, N. Y., Inc., has been named supply officer in command of the largest naval supply depot in New Guinea. Commander Williams was born in Leeds, England, in 1897. Before going to the Consolidated Edison Company in 1920 he had been associated with the Automatic Switch Company, New York, as draftsman, the Union Switch and Signal Company, Swissvale, Pa., and the Southern Pacific Railroad.

E. J. Thimme (A '27, M '29) assistant to the division superintendent, Passaic division, electric distribution department of the Public Service Electric and Gas Company, Paterson, N. J., has been made division superintendent in that division. Mr. Thimme started with the company in 1923 as a cadet engineer after his graduation from the Massachusetts Institute of Technology. In 1926 he was appointed engineer in the Passaic division, electric distribution department, and became division distribution engineer in that division in 1929. Seven years later he was made district superintendent, Passaic district, and when the Paterson and Passaic districts were consolidated in 1937, he was appointed assistant to the division superintendent.

F. A. Fleming (M '43) major in the Canadian Army and formerly in the test and engineering departments of the Canadian General Electric Company, Toronto and Peterboro, Ontario, Canada, recently has retired from the Army after serving six years as a technical staff officer. He has purchased an electrical engineering business in Ottawa, and will specialize in the sale and service of scientific and electrical instruments under the firm name of Sheppard Electrical Laboratories. Major Fleming was born in Toronto, Canada, and studied in the technical schools of Tóronto and the School of Applied Science and Engineering at the University of Toronto.

H. M. Jalonack (A '20, M '36) sales manager, central station division, General Electric Company, Schenectady, N. Y., has been appointed assistant to manager, transformer division. Mr. Jalonack entered the company's test division following his graduation from Syracuse University in 1917. Two years later he joined the general office organization. After spending four years in Schenectady and Pittsfield, Mass., in 1923 he was transferred to New York, N. Y., as district transformer specialist and served in this capacity until 1935 when he returned to Pittsfield as assistant sales manager, of the distribution-transformer and feeder-regulator section. He became sales manager of that section in 1942.

C. A. Butcher (M '22, F '43) formerly manager of the Pacific Coast manufacturing and repair department of the Westinghouse Electric Corporation, Oakland, Calif., has been appointed assistant general manager of the Crocker-Wheeler division, Joshua Hendy Iron Works, Ampere, N. J. Mr. Butcher is a native of Des Moines, Iowa, and was graduated from the Iowa State College with the degree of bachelor of science in electrical engineering. Following his early electrical experience with the Des Moines City Railway Company, he joined the Westinghouse company and has served in several capacities.

G. H. Woodard (M '42) manager of the aviation gas turbine division of Westinghouse Electric Corporation, Philadelphia, Pa., has received the company's Order of Merit in recognition of his creative engineering in the development of new products. Mr. Woodard was born in Schenectady, N. Y., in 1906 and received his degree in mechanical engineering from Cornell University in 1928. At one time he was associated with the Ingersoll-Rand Company at Phillipsburg, N. J. He joined the Westinghouse company in 1936 at the time of the formation of the new products division. He became manager of the new products division in 1941.

D. R. Shoults (A '35, M '42) formerly engineer of the aviation division, General Electric Company, Schenectady, N. Y., has been appointed vice-president of the Bell Aircraft Corporation, Buffalo, N. Y. Mr. Shoults was born in Storms, Ohio, and was graduated from the University of Idaho in 1925 with the degree of bachelor of science in electrical engineering. In that year he became associated with the General Electric Company. He is the author of a number of technical papers, and was engaged in a study of superchargers when he left for London in 1941 on a Government mission. He has served on several AIEE committees.

C. F. Miller (A '41) formerly a member of the electrical engineering faculty of Johns Hopkins University, Baltimore, Md., has been appointed chief engineer of Price Brothers Company, Frederick, Md. Doctor Miller received his bachelor degree from the Johns Hopkins University in 1935 and the degree of doctor of engineering from the same university in 1942. He has undertaken extensive research and experimentation work during the present war emergency with various electronic applications.

H. W. Tenney (A '23, F '43) assistant to the vice-president in charge of the Pittsburgh, Pa., divisions of the Westinghouse Electric Corporation, has been awarded the Order of Merit, the highest recognition for achievement given by that corporation. Mr. Tenney was born in Leominster, Mass., and was graduated from the Worcester Polytechnic Institute in 1920 with a bachelor-of-science degree and in 1922 he received the degree of electrical engineer. Mr. Tenney has been with the Westinghouse Corporation since 1920. He has served on several AIEE committees.

J. W. Carpenter (M '35) president and general manager of the Texas Power and Light Company, Dallas, has received the honorary degree of doctor of engineering from Southern Methodist University. Doctor Carpenter has been associated with many utility companies in Texas including the Corsicana Gas and Electric Company, the Athens Power and Light Company, the Dallas Power and Light Company, and the Texas Power and Light Company. Of the last-mentioned he became president in 1927.

J. S. Malsbury (A '33, M '39) captain, Signal Corps, United States Army, has been promoted to the rank of major. Major Malsbury, a member of the Reserve Corps since 1927, was ordered to active duty in 1942, and was stationed at Fort Monmouth, N. J., until July 1944. Then ordered overseas, he was first assistant theater radio officer in India, and in February 1945 he was made theater radio officer stationed near Kumming, Yumnan Province, China.

E. C. Brown (A '26, M '43) formerly assistant to the manager of the Connecticut Valley Power Exchange, Hartford, has been named manager. Mr. Brown graduated from the Massachusetts Institute of Technology in 1924 with the bachelor-of-science degree in electrical engineering. In that year he became tester for the United Electric Light Company, Springfield, Mass., and in 1925 was employed by the Connecticut Valley Power Exchange as assistant to the manager.

K. W. Miller (A '23, M '29) formerly senior engineer, Commonwealth Edison Company, Chicago, Ill., and former director of research of the Utilities Research Commission, has been appointed chairman of electrical-engineering research at the Armour Research Foundation of Illinois Institute of Technology, Chicago. Mr. Miller has done extensive work with oil-filled cables, and in the field of reduction of sheath loses on single-conductor underground power cables.

C. W. Mayott (A '13, M '43) formerly power expert of the Office of War Utilities, War Production Board, Washington, D. C., has resumed his position on the technical staff of the Hartford (Conn.) Electric Light Company. Mr. Mayott was instrumental in co-ordinating southeastern electric power plants, and will remain in the capacity of consultant for the Office of War Utilities.

P. S. Millar (A '03, M '13) president, Electrical Testing Laboratories, Inc., New York, N. Y., has been awarded the 1945 gold medal of the Illuminating Engineering Society. Mr. Millar is the second recipient of the medal established in 1943 in recognition of meritorious achievement which has conspicuously furthered the profession, art, or knowledge of illuminating engineering.

A. M. Musgrove, Jr. (M '37, F '45) lieutenant colonel, Corps of Engineers, United States Army, who is serving as chief engineer, utilities division, Camp Shanks, N. Y., has been awarded a certificate of commendation for his suggestion providing emergency lights at the exits of all post theaters in the event of failure of electric power.

H. O. Anderson (A '27) general sales manager, Rockbestos Products Corporation, New Haven, Conn., has been elected vice-president in charge of sales of that corporation. Mr. Anderson joined the corporation in 1927 to direct the sales, after being an agent in Boston, Mass., for Schweitzer and Conrad, Inc., Chicago, Ill.

J. L. Davison (A '43) on loan to the general engineering department, Aluminum Company of Canada, Montreal, Quebec, from

1937 until 1945, has returned to the Canadian Comstock Company, Ltd., Montreal, and has been appointed chief engineer.

F. M. Ogler (A '44) Philadelphia (Pa.) district manager, Trumbull Electric Manufacturing Company, has been appointed district manager of the Atlantic district, which now includes Maryland, Virginia, and the District of Columbia.

J. G. Glassco (A '03, F '28) retired general manager of the Winnipeg Hydro-Electric System, Manitoba, Canada, has been elected to honorary life membership in the Manitoba Electrical Association.

OBITUARY

John Somerville Highfield (F '42) consulting engineer, Highfield and Roger Smith, London, England, died August 15, 1945. Mr. Highfield was born in Cheshire, England, November 28, 1871, and received his education at King's College. He had a wealth of electrical experience having been associated with many enterprises including: Central Electricity Board; Borough of Dover Electricity Department; Cambridge Electric Supply Company, Ltd.; Charing Cross, West End and City Electrical Supply Company; South Wales Electric Power Company; Brompton and Kensington Electric Supply Company, Ltd.; Metropolitan Electric Supply Company; Edmundsons Electricity Corporation, Ltd.; Cornwall Electric Power Company, Ltd.; Imperial Continental Gas Association; Compagnie Continentale du Gaz; and the South Wales Aluminum Company, Ltd. Mr. Highfield's accomplishments were many. He designed and set up the first testing department for the Chloride Electrical Storage Company; supervised the erection of the power station at Stafford; invented the Highfield automatic reversible booster for controlling batteries; designed and constructed a power station, tramway and supply systems at St. Helen's, Lancashire. He made many addresses before professional societies, and was the author of many papers. His patent specification on "Improvements Relating to Pressure Relief Devices for Transformer Tanks and Like Containers" was accepted September 9, 1942. He was director, Central London Electricity, and of the London Power Company; past-president, Institution of Electrical Engineers, London, and past vice-president, Royal Institution of Great Britain.

Adolphus Mansfield Dudley (A '08, M '10, F '13) retired engineer, Westinghouse Electric Corporation, East Pittsburgh, Pa., died on August 16, 1945. Mr. Dudley was born in Cincinnati, Ohio, February 14, 1877, and received the bachelor-of-science degree in engineering in 1902 and the degree of electrical engineer in 1931 from the University of Michigan. Two years later he received the master-of-science degree from the University of Pittsburgh. Mr. Dudley began his professional career in 1902 as an erecting engineer, and two years later joined the Westinghouse Corporation. He successively held positions as control engineer; design engineer; commercial engineer; section engineer; engineering manager; engineering supervisor of development; manager of development engineering; marine application engineer; and engineering representative in the patent department. He retired early in 1944. He was author of "Connecting Induction Motors" and "Induction Motor Practice," and contributed the section on electric motors in the current Encyclopedia Brittanica. Some of his educational work was accomplished for the Engineers Council for Professional Development in its program of inspecting and accrediting schools of engineering. For three years Mr. Dudley was a member of the council of the Society for the Promotion of Engineering Education. In 1940 he was awarded the honorary degree of doctor of engineering by the University of Michigan for his contributions to professional engineering.

Max L. Kahn (A '20) chief engineer, General Electric Company, Ltd., Witton Works, Birmingham, England, died July 25, 1945. Doctor Kahn was born in Mannheim, Germany, in 1877, and subsequently became a naturalized British subject. He was educated at Karlsruhe University and was awarded his doctorate in 1902 for original work upon the characteristics of the contact resistance of carbon brushes. Early in his career he was associated with Brown Boveri and Company, Ltd., of Mannheim, and in 1904 was appointed chief designer of the Branch Engineering Company. Thence he proceeded to Witton as chief designer, succeeding to the post of chief engineer in 1933. During the 32 years he served the General Electric Company he was closely associated with the developments in electric machinery and was responsible for the design of some of the largest turbogenerators manufactured. He was a member of the Institution of Electrical Engineers, and collaborated with E. Arnold and J. E. LaCour in the preparation of a series of textbooks in seven volumes covering the design and construction of electric machinery.

Henry Girdlestone Acres (A '08, M '13) president, H. G. Acres and Company, consulting engineers, Niagara Falls, Ontario, Canada, died September 4, 1945. Born in Paris, Ontario, May 1, 1880, he was graduated from the University of Toronto with the class of 1903, and in 1924 was made doctor of science by the same university. From August 1903, to June 1905 he was assistant mechanical engineer for the Canadian Niagara Power Company, Ontario, and then did some special design and tunnel work for the Arizona Copper Company, Clifton. In September 1905 Doctor Acres became associated with the Hydro-Electric Power Commission of Ontario first as hydraulic engineer and later as assistant engineer, and at various periods served as its consultant. One of his accomplishments was designing the Shipshaw development of the Aluminum Company of Canada, Arvida, Quebec, and designing and supervising the Chippawa–Queenston development of the Hydro-Electric Power Commission of Ontario.

John M. Davis (A '34) transmission engineer, Indiana Bell Telephone Company, Indianapolis, and more recently a colonel in the Army of the United States, died August 13, 1945. Colonel Davis was born in Owen County, Ind., in 1905, and received a bachelor-of-science degree in electrical engineering from Purdue University in 1926. During 1926–27 he was a student engineer with the Indiana Bell Telephone Company, and for the next three years served as assistant engineer. In 1930 he took over the duties of toll-transmission engineer in charge of studies, field tests, and surveys on toll-plant transmission problems, engineering studies on radio, and special services. Colonel Davis entered on active military service in 1941 and went overseas in 1944, returning to the United States several months ago. While serving on Leyte Island he became ill. It was at that time he was awarded the Bronze Star Medal for his outstanding and difficult assignments for the Signal Corps.

MEMBERSHIP

Recommended for Transfer

The board of examiners, at its meeting of September 20, 1945, recommended the following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the secretary of the Institute.

To Grade of Fellow

Berberich, L. J., section engr., Westinghouse Research Labs., E. Pittsburgh, Pa.
Brown, F. S., elec. engr., Duquesne Light Co., Pittsburgh, Pa.
Crary, S. B., engr., analytical div., General Electric Co., Schenectady, N. Y.
Drake, C. W., asst. mgr., ind. engg. dept., Westinghouse Electric Corp., E. Pittsburgh, Pa.
Godsey, F. W., Jr., mgr., new products div., Westinghouse Electric Corp., Pittsburgh, Pa.
Hasmon, E., trans. engr., Pennsylvania Water & Pr. Co., Baltimore, Md.
Heintz, R. M., vice-pres. & secy., Jack & Heintz, Inc., Cleveland, Ohio.
Johnson, R. E., chief elec. engr., Barber-Colman Co., Rockford, Ill.
Kilgore, L. A., mgr., trans. & gen. div., Westinghouse Electric Corp., E. Pittsburgh, Pa.
Loughridge, C. H., cons. elec. engr., The Arcade, Cleveland, Ohio.
Monteith, A. C., asst. mgr., engg. depts., Westinghouse Electric Corp., E. Pittsburgh, Pa.
Pennney, G. W., mgr., electro-physics dept., Westinghouse Electric Corp., E. Pittsburgh, Pa.
Pinder, K., sr. elec. engr., E. I. duPont de Nemours & Co., Wilmington, Del.
Renshaw, D. E., engr., Westinghouse Electric Corp., E. Pittsburgh, Pa.
Strang, H. E., asst. to vice-pres., General Electric Co., Schenectady, N. Y.
Umansky, L., asst. mgr., ind. engr. div., General Electric Co., Schenectady, N. Y.
Van Sickle, R. C., design engr., Westinghouse Electric Corp., E. Pittsburgh, Pa.
Warner, R. G., vice-pres., United Illuminating Co., New Haven, Conn.

18 to grade of Fellow

To Grade of Member

Allum, J. A. C., mgr. director, Allum Electrical Co., Ltd., Auckland, N. Z.
Becker, H. E., supervisor, Westinghouse Electric Corp., San Francisco, Calif.
Bennon, S., elec. engr., Westinghouse Electric Corp., Sharon, Pa.
Booth, J. D., sect. engr., Westinghouse Electric Corp., Baltimore, Md.
Branson, N. G., des. engr., General Electric Co., Schenectady, N. Y.
Chaney, Y. T., ind. engg. dept., Trumbull Elec. Mfg. Co., Norwood, Ohio.
Crawford, C. H., sect. leader, General Electric Co., Schenectady, N. Y.
Curtis, T. E., chief engr., Southern States Equipment Corp., Birmingham, Ala.
Davis, W. C., chairman, elec. engg. dept., Penn College, Cleveland, Ohio.
Delfs, J. M., ind. engg. div., General Electric Co., Schenectady, N. Y.
Dole, A. R., assoc. tel. engr., Signal Corps, U. S. Army, Presidio of San Francisco, Calif.

Fels, O. B., Jr., elec. engr., General Electric Co., Schenectady, N. Y.

Fox, G. W., electronics ship supt., U. S. Navy Yard, Charleston, S. C.

Gardner, V. E., elec. engr., Bureau of Ships, U. S. Navy, Washington, D. C.

Gateka, F. F., elec. supt., Public Service Co. of Oklahoma, Lawton, Okla.

Geiger, W. H., div. engr., Public Service Elec. & Gas Co., Hackensack, N. J.

Hansen, E., asst. supt., production, Florida Power Corp., St. Petersburg, Fla.

Hoenie, N. J., asst. chief engr., Lincoln Electric Co., Cleveland, Ohio.

Horrell, R. F., des. engr., Westinghouse Electric Corp., E. Pittsburgh, Pa.

Hyde, G. C., pres., Gulf Public Service Co., Inc., & Louisiana Pub. Utilities Co., Inc., Dallas, Tex.

Johnson, L. L., project engr., General Motors Corp., LaGrange, Ill.

Krishnaswami, A. C. K., director, Seshasayee Bros., Ltd., Trichinopoly, S. India.

Kundel, T. Major, U. S. Army, Jefferson Proving Ground, Madison, Ind.

Lambert, J. S., Major, War Dept., Washington, D. C.

Leppert, J. H., tech. supervisor, Tennessee Eastman Corp., Oak Ridge, Tenn.

Lindemann, W. E., elec. engr., Tennessee Valley Authority, Wilson Dam, Ala.

Linden, C. A., engr., General Electric Co., Schenectady, N. Y.

Long, V. O., instructor, elec. engg., U. S. Naval Academy, Annapolis, Md.

Marra, E., application engr., General Electric Co., Schenectady, N. Y.

Mason, C. R., section leader, General Electric Co., Schenectady, N. Y.

McCandless, R. L., elec. supervisor, Boeing Aircraft Co., Seattle, Wash.

McMaster, R. C., research engr., Batelle Memorial Institute, Columbus, Ohio.

Meahl, H. R., elec. engr., General Electric Co., Schenectady, N. Y.

Merrill, J. R., sr. engr., Raytheon Mfg. Co., Waltham, Mass.

Miller, E. F., long lines dept., American Tel. & Tel. Co., New York, N. Y.

Miller, W. E., elec. engr., General Electric Co., Schenectady, N. Y.

Minocha, K. R., elec. adviser & inspector, Government of Cent. Provinces & Berar, Nagpur, India.

Moler, M. A., head, pr. equip. branch., U. S. Maritime Commission, Oakland, Calif.

Moore, L. M., engr., Central New York Power Corp., Syracuse, N. Y.

Moore, R. D., design engg., General Electric Co., Schenectady, N. Y.

Morgan, F., plant engr., Mercury Mills, Ltd., Hamilton, Ont., Can.

Morley, D. M., engr., General Electric Co., Schenectady, N. Y.

Mouat, T. W., Jr., asst. research engr., National Research Council, Ottawa, Can.

Peirce, R. M., research elec. engr., American Steel & Wire Co., Electrical Cable Works, Worcester, Mass.

Porter, F. M., elec. engr., American Gas & Electric Service Corp., New York, N. Y.

Quarles, L. R., assoc. prof., University of Virginia, Charlottesville, Va.

Ridgely, J., elec. engr., I-T-E Circuit Breaker Co., Philadelphia, Pa.

Roberts, F. C., engr., General Electric Co., Schenectady, N. Y.

Rodhouse, T. E., line des. engr., General Electric Co., Pittsfield, Mass.

Schwan, C. F., generator des. engr., Ohio Crankshaft Co., Cleveland, Ohio.

Sproul, R. T., member of technical staff, Bell Telephone Labs., Inc., New York, N. Y.

Story, T. H., adv. dev. engr., RCA Victor Div., Radio Corp. of America, Camden, N. J.

Walker, R. E., asst. chief des. engr., Smith & Gillespie, Jacksonville, Fla.

Wanamaker, R. L., elec. engr., General Electric Co., Schenectady, N. Y.

Weil, W. S., Jr., engr., General Electric Co., Philadelphia, Pa.

Whitehead, E. G., Lieut., U. S. Coast Guard Headquarters, Washington, D. C.

Williams, E. W., meter foreman, Montana Power Co., Butte, Mont.

Witzke, R. L., cent. station engr., Westinghouse Electric Corp., East Pittsburgh, Pa.

Yost, C. H., elec. engr., Curtis Publishing Co., Philadelphia, Pa.

59 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objecting to the election of any of these candidates should so inform the secretary before November 15, 1945 or January 15, 1946, if the applicant resides outside of the United States or Canada.

To Grade of Member

Beachley, R. W., Stone & Webster Engr. Corp., Knoxville, Tenn.

Brough, R., Telephone Manager's Office, Glasgow, Scotland

Brown, A. M., Commonwealth Edison Co., Chicago, Ill.

Brown, H. R., Corps of Engineers, Omaha, Nebr.

Claes, A. J., Socony-Vacuum Oil Co., East St. Louis, Ill.

Dave, N. M., New Standard Engg. Co., Ltd., Bombay, India

Derr, J. D., No. Carolina Shipbuilding Co., Wilmington, N. C.

Dibrell, J. W., Naval Ordnance Lab., Washington, D. C.

Eggert, C. J., Buckeye Laboratories Corp., Cleveland, Ohio

Fink, D. G., Electronics Magazine, New York, N. Y.

Fisher, J. T., Bell Tel. Co. of Canada, Toronto, Ont., Canada

Gelow, M. L., Graham Paige Motors, Detroit, Mich.

Haller, G. L., Col., Air Corps., Air Technical Serv. Cmd., Dayton, Ohio

Kellerman, W. C. (Re-election), Commonwealth Edison Co., Chicago, Ill.

Lean, J. W., Maj., Sig. C., AUS, Naval Research Lab., Washington, D. C.

Leiper, F. M., Berker & Wheeler, New York, N. Y.

Manfredo, L. H. (Re-election), Navy Yard, Bayonne, N. J.

Martin, H. W. (Re-election), Stevenson, Jordan & Harrison, Ltd., London, England

Mason, J., American Tel. & Tel. Co., Philadelphia, Pa.

May, G. C., U. S. Navy Dept., Minneapolis, Minn.

Meade, G. R., Reconstruction Finance Corp., Washington, D. C.

Parkinson, J. A., A. T. & S. F. Ry., Chicago, Ill.

Parnell, J. G., Board of Public Works, Niles, Mich.

Ray, J. H., Lt. Col., Engr. Construction Command, San Francisco, Calif.

Robertson, D. S., Dominion Government, Ottawa, Ont., Canada

Sands, L. G., Curtiss-Wright Corp., Bloomfield, N. J.

Ware, M. M., Sig. Corps, War Dept., Arlington, Va.

Wilder, H. F., Western Union Telegraph Co., New York, N. Y.

Zimmermann, F. O., Federal Tel. & Radio Corp., Chicago, Ill.

29 to grade of Member

To Grade of Associate

United States and Canada

1. North Eastern

Burnham, J. M., Eastman Kodak Co., Rochester, N. Y.

Cohen, A. M., Ward Leonard Elec. Co., Mount Vernon, N. Y.

Cunniff, T. W., Hazeltine Electronics Corp., Little Neck, L. I., N. Y.

Ewaskio, H., Jr., Great American Industries, Meriden, Conn.

Frohock, W. S., Sylvania Elec. Products, Inc., Danvers, Mass.

Lincoln, R. T., Binghamton Board of Education, Binghamton, N. Y.

Rossi, R. P., Gen. Elec. Co., Schenectady, N. Y.

2. Middle Eastern

Adair, J. M. (Re-election), Westinghouse Elec. Corp., Newark, N. J.

Ayllon, H. R., Gen. Elec. Co., Philadelphia, Pa.

Brown, A. (Re-election), Phila. & Reading Coal & Iron Co., Pottsville, Pa.

Chamberlain, E., British Air Comm., Washington, D. C.

Corcoran, J. P., Westinghouse Elec. Corp., Washington, D. C.

Danaher, J. J., Jr., Capt. U. S. Army, Nat'l Bureau of Standards, Washington, D. C.

Dreisbach, R. J., The Ohio Public Service Co., Port Clinton, Ohio

Geiger, F. M., Sperry Gyroscope Co., Inc., Baltimore, Md.

Gilky, E. W., The Glenn L. Martin Co., Baltimore, Md.

Gitschier, J. F., Pennsylvania Transformer Co., Pittsburgh, Pa.

Graham, M. A., Thomas & Betts Co., Elizabeth, N. J.

Hurford, A. C., Jr., Phila. Navy Yard, Phila., Pa.

Krantz, A. W., Reliance Elec. & Engg. Co., Cleveland, Ohio

Leaveley, C. D., Phila. Elec. Co., Phila., Pa.

Lichstein, M., Philadelphia Navy Yard, Philadelphia, Pa.

MacKinnon, J. D., Jr., Lt., USN, Bureau of Naval Personnel, Washington, D. C.

Moore, W. N., Jr., Simplex Radio Corp., Sandusky, Ohio

Owens, J. B., Westinghouse Elec. Corp., East Pittsburgh, Pa.

Pease, J. O., Rumsey Elec. Co., Washington, D. C.

Po-Wen, H., % Public Service Elec. & Gas Co., Newark, N. J.

Salko, J. R., Pa. Transformer Co., Pittsburgh, Pa.

Schwartz, L. S., Capt., Air Corps., Naval Research Lab., Washington, D. C.

Stone, J. C., Sperry Gyroscope Co., Inc., Phila., Pa.

Tyndall, J. T., Delaware Power & Light Co., Wilmington, Del.

Vidmar, J. F., The Ohio Bell Tel. Co., Cleveland, Ohio

Watson, H. A., Jr., Marine Equipment Co., Lakewood, Ohio

Wicher, W. E., Navy Ordnance Lab., Washington, D. C.

Wilson, S. A., Muse Art Engineering Corp., Philadelphia, Pa.

3. New York City

Bull, C. B. (Re-election), 129 East 69th St., New York, N. Y.

Dillon, S. V., Johns-Manville Sales Corp., New York, N. Y.

Ellis, H. J., Lt. (jg), USNR, — F.P.O., New York, N. Y.

Frankiewicz, S. A., N. Y. Navy Yard, Brooklyn, N. Y.

Santogrossi, D. J., Bendix Avia. Corp., Brooklyn, N. Y.

Stanton, R. L. (Re-election), Fed. Pr. Comm., New York, N. Y.

4. Southern

Anderson, O. E. E., Lt., USNR, Miami, Florida

Cutchins, A. P., Mutual Boiler Ins. Co., New Orleans La.

Johnson, M. D., Cabell Elec. Co., Jackson, Miss.

Lowe, H., Aluminum Co. of America, Atlanta, Ga.

Miller, N. J., Tennessee Valley Authority, Chattanooga, Tenn.

Rothwell, H. E., Va. Elec. & Pr. Co., Richmond, Va.

Sledge, L. N., Charleston Navy Yard, Charleston, S. C.

Ulm, R. W., Tenn. Eastman Corp., Oak Ridge, Tenn.

Warner, C. W. (Re-election), Ga. Power & Lt. Co., Valdosta, Ga.

5. Great Lakes

Rosenberg, J. J., Illinois Bell Telephone Co., Chicago, Ill.

Brown, H. L., Public Serv. Co. of No. Ill., Joliet, Ill.

Carman, W. L., Illinois Bell Telephone Co., Chicago, Ill.

Dibble, H. H. (Re-election), Indiana & Michigan Elec. Co., South Bend, Ind.

Duff, G. H., Westinghouse Elec. Corp., Peoria, Ill.

Dugan, K. L., General Motors Corp., Anderson, Ind.

Ewald, L., Jr., Ill. Bell Tel. Co., Chicago, Ill.

Farmer, J. D., Indiana & Michigan Elec. Co., South Bend, Ind.

Fuller, F. C., Jr., Illinois Bell Tel. Co., Chicago, Ill.

Garling, K. E., Fed. Elec. Co., Chicago, Ill.

Hansen, L. E., D. W. Onan & Sons, Minneapolis, Minn.

Hartman, C. J., The Commonwealth & Southern Corp., Jackson, Mich.

Hasselbacher, H. H., Chicago Burlington & Quincy RR Co., Chicago, Ill.

Massaro, A. V., Allis-Chalmers Mfg. Co., Springfield, Ill.

Miller, W. L., American Tel. & Tel. Co., Chicago, Ill.

Nibbelin, C. J., Commercial Solvents Corp., Peoria, Ill.

Parker, H. E., Electrical Testing Co., Peoria, Ill.

Sawicki, W. L., Winpower Mfg. Co., Newton, Iowa

Schwartz, F. N., Commonwealth Edison Co., Chicago, Ill.

Sedgwick, W. C., Central Illinois Light Co., Peoria, Ill.

Sievers, G. A., Line Material Co., South Milwaukee, Wis.

Stokes, H. L., Illinois Bell Tel. Co., Chicago, Ill.

Uliery, R. M., Indiana & Michigan Elec. Co., South Bend, Ind.

7. South West

Bell, R. A., Dallas Power & Light Co., Dallas, Tex.

Frohardt, A. E., Wagner Elec. Corp., St. Louis, Mo.

Gehlsen, R. G., Mines Equipment Co., St. Louis, Mo.

McNeely, J. S., Southwestern Bell Tel. Co., Dallas, Tex.

Sneed, J. W., Jr., Consolidated Steel Corp., Orange, Tex.

Steely, T. A., Fraser-Brace Eng. Co., Inc., Camden, Ark.

White, F. A., 1411 8th St., Lubbock, Tex.

8. Pacific

Bastow, W. R., Lt., USNR, San Francisco, Calif.

Bullis, W. R., Salinas Junior College, Salinas, Calif.

Burnell, H. L., Allis-Chalmers Mfg. Co., San Francisco, Calif.

Chapel, C. E., Northrop Aircraft, Inc., Hawthorne, Calif.

Dexter, G. W., University of California, Berkeley, Calif.

Fowler, L. S., Lt., USNR, Yard Public Works, San Francisco, Calif.

Hales, W. L., Solar Aircraft Co., San Diego, Calif.

Hodgson, R. W., Douglas Aircraft Co., Los Angeles, Calif.

Lehan, F. W., Calif. Inst. of Tech., Pasadena, Calif.

Murphy, D. M., U.S.E.D., San Francisco, Calif.

9. North West

Shaw, W. L. (Re-election), Utah Pr. & Lt. Co., Salt Lake City, Utah

10. Canada

Lewis, T. H., Hydro-Elec. Pr. Comm. of Ont., Burlington, Ont., Can.

Scroggs, S. H., Jr., Small Elec. Motors, Toronto, Can.

Shaw, D. T., Capt., Canadian Army, Montreal, Can.

Yeoman, A. R. A., Elec. Lt. Cmdr., RCNVR, Halifax, N. S., Can.

Elsewhere

Aziz Iskander, A., Atf Power Station, Mahmoudieh, Egypt

Craske, C. H., Imperial Chemical Industries, Ltd., Cheshire, England

Dalal, M. K., S. N. Paruck Parsi Polytechnic, Surat, India

Green, O. R., Electricity & Water Wks., New Amsterdam, B. G.

Pillai, K. N. R., Maj., Indian Posts & Telegraph Dept., Dacca, India

Rawal, C. A., Dept. of Industries, Govt. of Bombay, Daria Mahal, Surat, India

Sapiro, N. A., Asso. Elec. Engr., U.S.E.D., Ft. Armstrong, Honolulu

Tang, T. Y., Metropolitan-Vickers Elec. Co., Manchester, England

Total to grade of Associate

United States and Canada, 95

Elsewhere, 8

OF CURRENT INTEREST

5,000 New Products and Procedures From Atomic-Bomb Research

Immediate benefits to American industry in new inventions and new and improved products and procedures of manufacture resulting from the atomic-bomb project were foreseen recently at a luncheon meeting of business-paper editors held in New York, N. Y., under the auspices of The M. W. Kellogg Company, chemical engineers of Jersey City, N. J., and New York. The Kellogg Company arranged the meeting on behalf of its wartime subsidiary, The Kellex Corporation, a noncommercial industry-wide unit which engineered the designing, construction, and operation of the diffusion-process plant of the atomic-bomb project at Oak Ridge, Tenn. As a result of the inventive, scientific, industrial, and engineering advances incident to work on the atomic-bomb project, the Kellex Corporation estimates that more than 5,000 new and improved products and procedures are now available to American industry, awaiting only Government release for volume production.

The Kellex Corporation, which included in its personnel a cross section of the nation's scientific and engineering talent loaned for the war emergency by many companies, was formed for the purpose of developing procedure and designing equipment for volume production of uranium 235, the essential ingredient in the atomic-bomb project. The success of this undertaking and the technical soundness of the diffusion plant's processes and equipment are recognized in the announcement that, of the three methods in use at Oak Ridge it is the only plant which will be continued on normal operation. This decision, it is stated, was the result of a new postwar policy in which emphasis is shifted from all-out war production at any cost to concentration on a single process which would yield maximum peacetime production consistent with efficiency and economy of operation. Wartime performance of the diffusion plant was such that Government authorities selected this process alone for the separation of U-235 for postwar use.

The development work for this method had to be transformed from a highly theoretical concept without even a laboratory process upon which to base design and performance data into an efficient multistage commercial gas-recycling process. So vast was the undertaking and so enormous the cost that normally no single corporation or group of corporations would even consider industrial research on this subject with such little prospect of success.

The total cost alone of separating the U-235 isotope by the diffusion process in useful volume accounted for a substantial portion of the over-all figure of $2,000,000,000. The vast sum of money spent can be considered, according to the corporation, not only as a wartime necessity or as a preliminary to developing superpower resources in the future, but also as the Government's contribution toward the betterment of industry as a whole.

For industry does not have to wait for atomic power to utilize the experience of the project. Many lessons have been learned which can and will be applied immediately to more efficient processing. All these lessons cannot be revealed, at present, but they are in the minds of engineers and firms participating in the project and will be inextricably bound up with their future thinking, engineering design, construction, and processing. Some items in these fields can be mentioned and will afford some idea of the enormity of the problem and the scope of its application toward the betterment of industry.

The following partial list of industries gives some indication of how they will benefit from knowledge gained in the U-235 problem:

1. Petroleum refining.
   (a). Improved pumping.
   (b). New-type more efficient heat exchangers.
   (c). Mass spectroscope (continuous analytical control).
   (d). Possible new methods of separating gasoline fractions.
   (e). Improved automatic control.
2. General chemical and processing industries.
   Same improvements as in petroleum refining.
3. Manufacture of pressure and vacuum vessels.
   (a). Checking welds.
   (b). Pretesting vessels for leaks before operation.
   (c). Improved vacuum techniques.
4. High-vacuum industries.
   (a). Improved vacuum methods for vitamin distillation.
   (b). New methods of detecting high vacua in electronic-tube manufacture.
   (c). Low-pressure low-temperature dehydration of foodstuffs.
5. Gas-processing industries.
   (a). Diffusional separation of helium from natural gas.
   (b). Efficient separation of hydrogen from process gases.
   (c). Diffusional separation of oxygen and rare gases from air.
   (d). New techniques in gas recycling.
6. Electrical industry.
   (a). New electronic techniques in high vacua.
   (b). Improved microsensitive instrumentation.
7. Medical profession.
   (a). A low-cost more abundant source of radioactivity.
   (b). Improved protective methods for combatting toxicity in industry.
   (c). Extension of cancer therapy.
8. Refrigeration industry.
   (a). Increased safety in equipment.
   (b). Improved handling of fluorides for refrigerants.
9. Industries employing corrosive chemicals.
   (a). New pump and valve lubricants and packing methods.
   (b). New treatment of metal surfaces to prevent corrosion.
   (c). Improved safety practices.
   (d). Completely enclosed pumps operated from exterior by induction.

CORROSION FACTORS

From the start the project encountered staggering obstacles. Uranium, being a solid, had first to be transformed into a gas for utility in the selected gas-diffusion process. This meant selecting a compound of uranium with some other element which would be gaseous at nominal temperatures and from which elemental uranium could be regained readily after diffusion. After much experimentation, which included uranium hexafluoride, UF_6, and other gases, suitable process gases were selected. One of the major advantages of UF_6 which brought it into special consideration was that fluorine, having only one isotope, would not complicate the separation by adding new combinations which would diffuse at varying speeds. Uranium hexafluoride is a solid at room temperature but fortunately turns into a gas at 56 degrees centigrade. Unfortunately, however, like most fluorine compounds, it was highly reactive, physiologically poisonous, and introduced problems of corrosion which pointed toward difficulties in production and handling. In the words of one Kellex spokesman "uranium hexafluoride is one of the hardest things to handle in the history of mankind."

It was found that practically all the techniques and developments gained in the successful study of the problem could be carried over into a number of industries plagued by corrosion factors through improvement in equipment and processing. The results indicated a saving of millions of dollars annually in the conservation of critical equipment and materials, minimum breakdown of moving parts, and increased safety for workers.

In the process it was imperative that no material in contact with the process gas react with it, as such corrosion would lead not only to plugging of the microscopic pores of the diffusion barrier and various mechanical failures but also to absorption (that is, virtual disappearance) of enriched U-235 isotope. Obviously, therefore, standard-type valves and piping could not be used; instead, new methods of pretreating metal surfaces against corrosion were worked out, new coolants, piping, new-type heat exchangers, lubricants, pumps, and packing were developed to satisfy the stringent requirements.

APPLICATION OF NEW CORROSION KNOWLEDGE TO INDUSTRY

Hydrogen fluoride is an important isomerization and alkylation catalyst in petroleum refining, as well as an important raw material in the production of aluminum and refrigerants. It is, however, so highly active and dangerous that industry has not yet capitalized on many of its potentialities. Its handling now may be made safer and simpler without excessive maintenance costs, and as a result its increased use in industry may be realized.

Other important starting materials for a host of industrial products, such as sulfur dioxide, hydrogen chloride, and the mineral acids (sulfuric, nitric, and phosphoric), all have presented severe problems of transfer and corrosion with particular emphasis on valve lubricants and pump packings. These difficulties can be simplified greatly by application of the knowledge gained through the extensive experimentation with UF_6 and the other related gases.

PUMPS

The story on pumps, the heart of the process and one of its most difficult problems, is particularly interesting and applicable to modern industry. Thousands of pumps operating under reduced pressure at Oak Ridge created problems in vacuum technique on an unheard of scale. Other thousands operated at nominal pressures. But regardless of the type or service none could leak or corrode, and all had to have as small a volume as possible. Many different types of centrifugal blower pumps and syphon-sealed reciprocating pumps were tried out and new types developed. For example, in one of the pumps for the larger stages the impeller was driven through a coupling containing a very novel and ingenious new seal. Another type of pump was completely enclosed, its centrifugal impeller and rotor being run from the outside by induction.

Top-flight pump designers from leading manufacturers in this country collaborated in research at the central Kellex laboratories in Jersey City and succeeded to a remarkable degree in increasing industry's knowledge of this all-important phase of processing. For security reasons the practical applications of the new types of pumps developed cannot yet be disclosed publicly. However, the engineers who participated in this phase of the project have brought to their parent companies a vastly increased lore of new techniques which cannot help but be reflected in increased service to their customers.

Perhaps the most significant advance in pump design which has been accomplished most successfully is the utilization of supersonic velocities of a very high order (Mach numbers of over 1.0).

BARRIER REQUIREMENTS

Literally acres of porous barriers were required for the gas diffusion plant with billions of holes smaller than 0.01 micron. Despite the high degree of porosity required, such barriers had to be able to withstand a pressure head of one atmosphere. The pores had to be of uniform size and spacing and could not become enlarged or plugged up as the result of direct corrosion or dust coming from corrosion elsewhere in the system, and the barriers had to be adaptable to manufacture in large quantities and with uniform quality.

One of the chief reasons for the lack of diffusion techniques in industry today has been the barrier problem. Few, if any, corporations cared to expend the prohibitive time and money in the necessary research on this problem, until it was made necessary by the exigency of the situation. Almost at the last minute an excellent barrier was developed, and today these operate successfully throughout the more than several thousand stages.

APPLICATION OF DIFFUSION PRINCIPLES TO INDUSTRY

Now that a large part of the basic research on diffusion barriers and their application to full-scale industrial separations has been completed, particularly with reference to gas recycling and instrumentation, the next development would seem to be the separation of helium from natural gas by diffusion techniques rather than by the present refrigeration method. Helium is so light in comparison to other components of natural gas that its diffusion velocity through a porous barrier is over twice as great as the next lightest compound present in the same source.

It may be still easier to isolate hydrogen by these new methods from a number of process gases now used merely as fuel, because the diffusion velocity of hydrogen, the lightest of our elements, is over four times that of any compound associated with it.

The isolation of ethylene by incorporating diffusion barriers as an integral part of cracking units conceivably could supply an abundant source of this versatile chemical used for the manufacture of synthetic rubber, plastics, antifreeze, alcohol, and many other products.

The preparation of oxygen and rare gases from air without resorting to refrigeration and fractional distillation is another possible application, when economic methods are developed.

The direct isolation of natural gasoline fractions from crude petroleum without resorting to distillation, and new types of fractionating columns for the petroleum-refining industry also appear feasible.

INSTRUMENTATION

If pumping is the heart of processing, then instrumentation is the brain. No continuous process could function efficiently without adequate automatic control. In the gaseous diffusion plant the problems of instrumentation were far greater than in any other industry, because the theory involved the assumption that diffusion took place through an infinite number of stages, whereas practicability dictated that such stages be limited in number.

Even so, several thousand stages were required, necessitating an intricate system of gas recycling involving abnormally large volumes of gases in relation to the finished product and continuous high-precision analytical control. About half of the gas processed in each stage diffused through the porous barrier as enriched U-235 product and after repressuring was sent on to the next higher stage for further concentration; the impoverished half also was repressured and recycled through the next lower stage. The recycling involved was enormous, over 100,000 times the volume of the final enriched gas.

There were developed to meet these needs the most precise continuous automatic analytical control instruments ever produced by man, it is claimed. This refinement is one of the outstanding features of the gas-diffusion plant and constitutes one of its most important applications to industry today. Instruments which before had existed only in research laboratories were improved upon and adapted to commercial use; completely new prototypes were conceived, developed, and put into mass production. The result is that now there is available to industry a more nearly perfect system of continuous automatic control than ever has existed.

APPLICATIONS OF NEW INSTRUMENTATION TO INDUSTRY

Mass Spectroscope. One of the developments employed is a new type of mass spectroscope, which every petroleum refiner will welcome for control of cracking operations and transfer line analysis. The mass spectroscope has been employed for several years in research laboratories and even within the last two years in certain phases of the refining industry but never on the perfected scale developed at Oak Ridge. The foremost instrument engineers and physicists in the United States and England devoted their full time not only toward gearing this instrument to continuous control but also to expanding United States capacity for its quantity output. In no other country has electronic research been applied on so grand a scale. The mass spectroscope is an electronic device for analyzing gases both qualitatively and quantitively from a mass standpoint by separating a beam of dissimilar gas molecules into separate beams according to their formula weight. Determinations are very fast, require only a thimbleful of gas, and make obsolete the formerly used Orsat and chemical analyses, particularly for the purposes of continuous control where instantaneous changes must be effected the moment a process swings off the line.

Its potential uses in industry include the accurate analysis of natural gas or any process gas; the continuous automatic control of any gaseous process such as alkylation, dehydrogenation, vapor phase cracking, and so forth; the checking of inert gases such as nitrogen used to provide a protective atmosphere in furnaces and so forth; the checking of the completeness of any evacuation process, as in the manufacture of radio tubes; the detection of impurities; and many others. Industry will not have to wait for benefits from this versatile tool, because production facilities have been increased enormously since the new type was created.

Leak Detector. A second development, aptly and simply called the leak detector, is more sensitive than any other existing device previously utilized for the same purpose. It played an important part in ensuring that all parts of the gaseous-diffusion plant were vacuum tight. Any leaks out of or into the system would be damaging both from the standpoint of loss and of contamination of an exceedingly valuable material. The leak detector is well adapted for locating annoying leaks in industrial high-vacuum processing industries, such as vitamin manufacture, in which even microscopic leaks undetectable by the familiar ammonia-hydrogen-chloride method or Tesla coil method are still potent enough to prevent drawing the necessary high vacuum on the equipment. Other potential uses include the pretesting of pressure and vacuum apparatus before putting it in service, checking equipment in operation to ensure no wasteful loss or contamination, the testing of welds for minute pores which otherwise would escape detection, and ensuring the physiological safety of refrigeration equipment employing toxic coolants.

Heat Exchangers. Of great interest to the petroleum-refining industry is the development of a new-type heat exchanger. Since

an unavoidable concomitant to pumping gas is heating it and since enormous volumes of gas were processed, individual cooling units for each stage had to be developed. A brand new type of heat exchanger was conceived for this purpose and developed up to the production stage. A manufacturer then was selected and shown how to make it, even to the extent of redesigning his equipment so that thousands of units could be turned out quickly. The units were installed and functioned very well.

POSSIBLE MEDICAL AND PHYSIOLOGICAL BENEFITS

Because of the variety and multiplicity of radioactive products which can be produced by means of U-235, humanity faces the prospect of soon having available for therapeutic medicine radioactive materials possessing a wide variety of properties. It is logical to expect, therefore, that these new materials will be suitable for products offering a greater range of usefulness, and at a lower cost than radium.

The possibility exists of incorporating a micro quantity of a radioactive isotope in food to observe its metabolism in the body of experimental animals. Such tagged material could be traced readily in its passage through the organs of the body.

MONEY NOT WASTED

Kellex representatives urged that it be borne in mind that the afore-mentioned benefits accruing to American industries as a result of knowledge gained in the development of the gas-diffusion plant represent only a small part of that permitted to be revealed at this time. The total cost of the project, $2,000,000,000, actually only represented eight days of war cost to the United States.

If it be estimated that the war would have lasted another six months the actual saving could be estimated at $45,000,000,000.

Latest Army Radar Set Guards Coasts and Guides Ships

Existence of seacoast fire-control radar, a new set, which it is claimed "will revolutionize our coastal defenses" and will guide incoming ships, even those without radar equipment, to port through fog and darkness, recently was revealed by the Army.

The apparatus was designed by the radiation laboratories at Massachusetts Institute of Technology, Cambridge, for the Army Signal Corps, and sets had been in operation along United States coastlines and on the coast of Iwo Jima before the war ended.

Detection of vessels at least 25 miles at sea with a definition hitherto impossible for shore-to-sea sets has been accomplished with the new apparatus. Its accuracy of definition is within five yards in any direction at the effective firing range of 12 miles. Used for nonmilitary purposes, it will allow the safe guiding to anchorage of ships which either lack radar entirely or have equipment that is out of commission. The shore radar operator, possessing what amounts to a motion-picture view of the approaching ship in his radar oscilloscope, can warn the ship by radiotelephone of all obstacles in its path.

As a defense weapon the new set enables accurate nighttime firing, because the radar automatically relays information on range and bearing of the target to the guns. Such a degree of definition has been secured in sighting objects that a fleet of several hundred large and small ships, detected at a distance of 30 miles, shows up as separate dots of light, and an area of one mile square can be brought to such magnification that a ship five miles away can be seen to turn, and sometimes can be identified as to class.

A unique feature of the new set is the extremely narrow beam of radio pulses which it emits—one half of a degree wide. At a range of 5,000 yards the beam is only 50 yards wide. Surveillance radar sets formerly used to scan the sea from land employed beams that were 60 to 80 times as wide.

EDUCATION....

Educational Advantages for Veterans

Rensselaer Polytechnic Institute, Troy, N. Y., recently announced a co-operative plan with industry to aid in replenishing the nation's supply of scientific and technological personnel.

According to Livingston W. Houston, president of the institute, the General Electric Company has agreed to participate in training as many as 80 men at a time as its share in the program and other nationally known companies also are arranging to take part.

The plan is said to differ from the average college-industry plan in that it will carry students through at least to the master's degree and enroll only those who indicate talent and ability for graduate study and research. Rensselaer Polytechnic Institute and the co-operating industry will select the candidates jointly from the regular student body in their sophomore year.

The program will get under way November 1. While studying various branches of engineering, physics, and chemistry, students will spend about 30 per cent of their time in shops or laboratories of the industries, for which they will receive wages. Neither the student nor the company is obligated, one to the other, as to later employment.

The plan will enable veterans to receive a high standard of education in cases where, because of dependents, the educational benefits of the "GI Bill" would not otherwise be sufficient.

The institute will also open on November 1, 1945, a program of co-ordinated evening courses leading to baccalaureate and graduate degrees as well as individual courses in independent subjects. The work covers engineering, science, management, English, literature, history, and economics. This plan will likewise offer an opportunity to veterans who find the financial allowances under the bill insufficient to permit them to go to college without working at the same time.

MIT to House Returning "GI's." The Massachusetts Institute of Technology, Cambridge, will build 100 houses for married veterans who are planning to resume their education this autumn or in the spring of 1946. The decision to build came after a survey of housing conditions and facilities of Greater Boston showed that it would be practically impossible for a veteran returning to the college to find suitable living quarters. The departments of civil and mechanical engineering provided advice on grading, roads, paths, drainage, and electric layouts for the houses which will be erected on land belonging to the institute and adjacent to it.

Polytechnic Institute of Brooklyn Aids Veterans

A series of eight degree-guidance circulars has been prepared by the Polytechnic Institute of Brooklyn, N. Y., as a means of giving specific information to the many inquirers from all parts of the world. Each of the circulars is devoted to a full outline of the four-year requirements leading to the bachelor degree in electrical engineering; aeronautical engineering; chemistry; chemical engineering; civil engineering; mechanical engineering; metallurgical engineering, and physical science.

To assist returning veterans, Polytechnic Institute in the spring of 1945 set up a counseling service for the use of men already separated from service and for men who were still in service and who wanted to know what requirements they must meet. During the past academic year the institute had an enrollment of 136 veterans. In the autumn of 1943 veterans at the institute organized the first chapter of Gamma Iota Alpha, the "GI" association now expanding as a collegiate veterans' association in college chapters throughout the United States.

Two curricula are now available at the institute in electrical engineering, one featuring power and industrial applications and the other communications and electronics. They include new courses in electrical controls, power systems, electromagnetic fields, and electroacoustics.

Fellowships Granted by Eastman Kodak

To assist universities in reducing the post-war dearth of young men with advanced technical training, the Eastman Kodak Company, Rochester, N. Y., will expand its granting of annual fellowships into a program of aid to graduate students of chemistry, physics, mechanical and electrical engineering, and business administration. This enlarged program is to provide 12 fellowships for doctoral work and ten fellowships for masters' work. The previous Eastman Kodak grants, numbering only six, were confined to the field of chemistry and chemical engineering.

Of the awards to be granted persons pursuing doctoral training, one fellowship is designated for chemical engineering at the Massachusetts Institute of Technology, Cambridge, Mass., another is for work in organic chemistry at the University of Illinois, Urbana, and another is for the study of physical chemistry at the University of Rochester, Rochester, N. Y. The nine other fellowships for doctoral work—six in chemistry and three in physics—are to be rotated among various universities from year to year.

To encourage graduate training in the field of mechanical engineering, the Eastman

Kodak Company is offering four fellowships to men majoring in design in work toward their master's degree. It is planned that two fellowships will be awarded, in addition, to students completing their master's degree in electrical engineering. The company's interest in this field has evolved largely from its increasing concern with the application of the principles of electronics and electrical engineering. These six fellowships are to be utilized at different universities each year.

A major purpose of the increased fellowship grants is to augment the research activity of the universities, thus raising the quality of instruction and enhancing the training of students becoming available for industrial positions.

Special Courses for Veterans at Stevens and Columbia

A pre-engineering training course for veterans desiring to study engineering who have not completed the required preparatory studies or who wish to review high-school subjects before starting college work in engineering has been organized by Stevens Institute of Technology, Hoboken, N. J. Regular faculty members will supervise the instruction in physics, chemistry, mathematics, and English which will comprise the course.

For veterans who intend to operate small businesses and have insufficient time for a full college program, Columbia University has designed an eight-week intensive course to be given by the school of business and university extension. Students will receive instruction in the fundamentals of accounting, finance, marketing, organization, buying and inventory control, advertising, labor relations, booms and depressions, risk and insurance, taxation, planning and budgeting, and business policy, as well as special instruction in the operations and problems of particular types of small business. Classes will be supplemented by panel discussions led by men experienced in operating small business or men who are specialists in serving small business.

Technical Subjects Urged for Schools. The vocational high school division of the schools of New York, N. Y., has prepared a report urging the introduction of technical courses in ten of the city's trade schools. If approved this plan would offer technical training at the secondary-school level to a larger percentage of students, and would prepare students for posts as vocational technicians or for admission to engineering colleges. The report noted that during the period of rapidly changing economic and technological conditions, an attempt, already started, should be continued to train boys and girls to meet these conditions.

Television at Syracuse. Syracuse University, Syracuse, N. Y. has reserved an "Intra-Tel" system—wired television—from the General Electric Company, Schenectady, N. Y., for postwar delivery. William Pierson Tolley, chancellor of the university, said that the television equipment will be used to conduct various classroom teaching experiments, as well as teaching television programming and other techniques to students. He said that Syracuse University students would be given the opportunity of studying various television operations such as script writing, costume and stage-set designing, lighting, camera operation, stage and technical direction, picture and sound control and other transmitter operations, and that the university's experience would be made available to other educators.

Educators Inspect Navy Postgraduate School

A group of recognized engineering educators recently was invited by the chief of naval personnel to visit the United States Naval Postgraduate School at Annapolis, Md., for the purpose of inquiring into the character and scope of instruction, and to offer suggestions for the arrangement of the Navy's postwar plans for graduate education of its officers. The group which included W. B. Kouwenhoven (F '34) dean, school of engineering, Johns Hopkins University, Baltimore, Md., also considered the propriety of authorizing the master-of-science and doctor-of-science degrees to student officers who fulfilled established requirements.

The postgraduate school was established at the academy in 1909 with the purpose of offering advanced technical education to meet specific naval needs. In the interests of furthering its educational program, the Navy Department has granted authority to the postgraduate school to participate in a program for an exchange of professors with selected colleges and universities.

Survey of Latin America Engineering Education

Dean S. S. Steinberg of the college of engineering, University of Maryland, College Park, will return to the University late this month from a good-will tour of Latin America made in the interest of engineering education. He traveled as the guest of the State Department in behalf of its division of cultural cooperation.

The purpose of his trip was to make a survey of engineering education in the American republics; promote closer relations between the engineering educators of Latin America and the United States; arrange for exchange of professors, and provide for a wider interchange of engineering and technical publications.

For this trip Dean Steinberg was designated official representative of the Society for the Promotion of Engineering Education.

Electrical Engineering for Service Men. A survey recently undertaken by Professor B. A. Thresher, director of admissions, Massachusetts Institute of Technology, Cambridge, revealed that a majority of the service men interested in an engineering education picked electrical engineering as their foremost interest. The admissions director was impressed by the extent to which the service men have been influenced in planning their engineering-education careers by the type of work they have been doing in the Army and in the Navy. He interpreted the choice in electrical engineering over the other branches of engineering to the fact that the men tend to choose that vocation which seems to them of most immediate practical significance.

Education for "GI's" in Europe. More than 1,000,000 men stationed in Europe have responded to the program of the War Department for an educational plan that will be broad and of practical value when the men return to civilian life. Schools have been organized so that soldiers of varying levels of education can continue their schooling in both academic and in technical subjects. The latter will utilize Army equipment and offer advanced training in such fields as radio, photography, and various types of engines. American colleges and universities have co-operated and business corporations have furnished instructors and materials. The majority of the teachers, however, will be recruited from officers and men now in the Army but a number of leading educators from the United States have agreed to help get the program under way.

Training in Aeronautical Developments. The aeronautical and marine technical school, of the General Electric Company, Schenectady, N. Y., designed to train both civilian and military personnel in installation, maintenance and repair of new fighting equipment, has graduated a total of 559 since inception of the school in 1942. Of the total, 220 have been United States Army and Navy instructors and supervisors, 239 have been engineers of the company and 100 have been representatives of manufacturers. Now in its fourth year, the school has evolved mainly to keep the military abreast of and trained in the use of new aeronautical developments, and to provide scientists of the company and other civilian scientists with a wider and more practical scope of the field and its problems.

Aeronautics Program at Princeton. The School of Engineering, Princeton University, Princeton, N. J., will initiate its first formal graduate-teaching program of its department of aeronautical engineering in November 1945. Emphasis will be placed on those phases of aeronautical science which have been advanced during the war period. Fundamentals will include study of aerodynamic theory, vibrations, and elasticity, and special consideration will be given to such topics as the aeronautical applications of jet propulsion and gas turbines, and modern techniques of flight testing and structural research.

Navy V-12 to Continue at Hoboken. The Navy V-12 training unit at Stevens Institute of Technology, Hoboken, N. J., will be continued with a quota of 377 men after November 1, 1945. Stevens was designated for the training of engineers at its own request under the Navy College Training Program on July 1, 1943. More than 900 men

have received training at the unit, and 292 men have been graduated under the V-12 program since its beginning at the institute. Upon completion of the course, and after postgraduate studies at midshipmen training centers, the V-12 students are given commissions in the United States Naval Reserve. Although the general policy of the Navy had been to consolidate the program at the end of the summer term of 1945, certain units having Naval Reserve officers-training-corps components, marine detachments, and substantial numbers of upper-level engineers are being continued.

Education Via University Radio. A university radio council to co-ordinate radio activities at Columbia University, New York, N. Y., and to "put education on the air" through its own radio station is a plan of the university announced recently. The university's application for a frequency-modulation radio station has been filed with the Federal Communication Commission, Washington, D. C. The council will be composed of representatives of various schools and divisions of the university, and will be responsible for the control and administration of radio activities. Doctor Russell Potter, chairman of the university's radio committee, declared that through radio Columbia University anticipates bringing to a much larger audience the intellectual, cultural, and scientific resources of the university. It is proposed to broadcast a minimum of six hours daily afternoon and evening throughout the academic year. The station will be on the campus with its transmitter in Alpine, N. J.

RESEARCH • • • • •

Science Offers Choice—Sarnoff

Life or death is the choice facing mankind today as a result of scientific research developed over the past several years and exemplified in today's fateful weapons for war or peace. This is the belief of David Sarnoff (M '23) president, Radio Corporation of America, New York, N. Y., and brigadier general, United States Army, whose article "Science for Life or Death" appeared in the August 10, 1945, *New York Times* with the approval of the War Department.

General Sarnoff urges constant vigilance on the part of the Government of the United States to marshal science and industry to defend itself against aggression. This means not only military preparedness but also scientific preparedness. He urges the engaging in research of the scientific talent of the United States not only in wartime but also in peacetime in order to find the solutions to scientific problems from as many angles as possible claiming that there cannot be too many laboratories. Asserting that the vital role science can play in peace or war for the future calls for consideration of its potential influences upon the territorial, economic, social and political problems that nations seek to solve, General Sarnoff concludes that the "voice of science should be heard in the halls where the architects of peace design our future."

Expansion at University of Pennsylvania. The Moore school of electrical engineering, University of Pennsylvania, Philadelphia, will be enlarged at a cost of nearly $125,000 as a step in the development of its long-established program of engineering research to aid industry, public health agencies, and the United States Army and Navy, according to Harold Pender (F '14) dean of the school. The additional laboratory area will be adapted for research in various phases of electronics, such as television and industrial control, and will be used also for the investigation of problems related to electric machinery. He said that before the war the Moore school laboratories were equipped for both educational and research work in all branches of electrical engineering, and as student enrollment decreased during the war much of this equipment was used for research projects assigned to the school by the United States Government. Many of these projects are being continued while the school is experiencing a steady increase in student enrollment in electrical engineering. Hence the need for additional laboratory space.

New Rubber Silicones. "Silastic" is the latest group of high polymeric organo-silicon oxide polymers to develop from laboratory research into commercial production by Dow Corning Corporation, Midland, Mich. This new silicone rubber now provides a group of engineering materials which remain elastic and compressible at temperatures of 150 degrees centigrade for long periods and can be used at temperatures up to 250 degrees for certain applications. The temperature limitations of natural rubber long have been realized and many attempts have been made to impart to the new organic synthetic rubbers the qualities of increased thermal resistance. In many instances these efforts have been successful in raising the safe operating limits of rubber or synthetic-rubber insulations.

Centers for Oil Research. Plans for construction of two petroleum research centers, one in Linden, N. J., and the other at Baton Rouge, La., were announced recently by Eugene Holman, president of the Standard Oil Company of New Jersey. He said that the program would provide scientists of the Standard Oil Development Company, the central technical organization of Standard Oil Company of New Jersey, with modern and extensive research facilities in the oil business. R. P. Russell, president of the Standard Oil Development Company, said the new laboratories would be used not only for developing improved products from oil and processes for producing them, but also for much work in extending sources of supply of oil products, including gasification of coal, oil from coal, and production of oil from other carbonaceous products.

Research on Steel Planned. A $5,000,000 postwar research and production expansion program has been approved by the board of directors of the Allegheny Ludlum Steel Corporation, Pitsburgh, Pa. A modern research laboratory and related experimental and pilot-plant equipment will be built at Brackenridge, Pa., to intensify studies of the structure, melting, processing, and further development of high alloy steels. A cold-rolling mill of latest design, for rolling stainless and silicon strip steels will be constructed at West Leechburg, Pa.

Starts Work on Research Center. Construction has been started on the research laboratories of the Navy Bureau of Ordnance, White Oak, Md. When completed this project and the Glenn L. Martin College of Engineering and Aeronautical Sciences of the University of Maryland will form one large center of research in the fields of physics and engineering. Captain W. G. Schindler will be in command and Captain R. D. Bennett (F '35) will direct the research.

INDUSTRY • • • • •

Course in Quality Control Methods At Iowa City

An intensive ten-day course, "Quality Control by Statistical Methods," to be given November 6–16 inclusive, was announced recently by F. M. Dawson, dean of the college of engineering and chairman of the committee on quality control, and by Earl J. McGrath, dean of the college of liberal arts, State University of Iowa, Iowa City. The University of Iowa has co-operated with the War Production Board and the United States Office of Education in giving similar courses in quality control by statistical methods.

A feature of the proposed course is a follow-up program in which two two-day clinics will be held with industrial representatives to discuss common problems and to obtain additional information. The course is designed for executives and persons in an advisory position where the knowledge gained can be applied immediately. Tuition for the course, including books and supplies, is $100. Trainees will be expected to provide for their own living expenses and transportation to and from Iowa City. The number of trainees in the course will be limited.

Bendix to Stimulate Foreign Trade. The formation of a new division, Bendix International, to handle the foreign-trade program of Bendix Aviation Corporation, New York, N. Y., has been announced. It will be under the direction of Charles T. Zaoral, general manager, who joined the corporation in January as co-ordinator of foreign affairs, after many years of experience in the foreign field for General Motors Corporation and Dodge Brothers, Inc. The new division will handle throughout the world, with the exception of the United States and Canada, the products of the 17 divisions of the corporation. It has established headquarters at the corporation's New York office and will maintain engineering, sales and service personnel to develop opportunities for two-way international trade.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Role of AIEE in Professional Relations

To the Editor:

In the June and July issues of *Electrical Engineering* are three thoughtful papers, each concerned with the questions—who or what shall become the voice of the profession. Mr. Fairman, in "Organization of the Engineering Profession" (*EE, June '45, p. 220–3*), forthrightly proposes that each individual member of the Institute join the National Society of Professional Engineers. The subcommittee on civic affairs, in "Civic Responsibilities of Engineers" (*EE, July '45, p. 257–2*), suggests the formation of a local engineering council, or club, or society composed of representatives of the local chapters of the national engineering societies and other local technical organizations. The committee on collective bargaining and related matters in "AIEE Report on Collective Bargaining" (*EE, July '45, p. 239–45*) says that an organization of engineers, an association of engineers and employees in closely related professions, and an organization of all professional employees are suitable forms of labor organizations for engineers.

In each case the suggestion is that somebody other than AIEE represent the electrical engineer.

In each case the argument is presented convincingly. Granted then that the role assigned to AIEE administration—the elected and appointed officers of the electrical engineering democracy—is that of a sort of *pater familias* guiding and advising his progeny in their jousts with the outer world, what kind of an Old Man of the Mountain should we develop? Should he be a long-haired, gray-bearded recluse delivering his oracular pronouncements from the shadows of his cavern or castle after being properly propitiated, or should he be a vital, barrel-chested, whooping head-of-the-family ever ready to enter the field of battle with the required club or shield to be shoved into the hands of his sons or even to be used in their behalf? I prefer the latter.

If the common preference is such then AIEE owes its members positive action. If the Fairman recommendation is good—and I for one support it—then AIEE should act by urging and helping its members to obtain professional licenses; by channeling some of its talent into the administration of the National Society of Professional Engineers so as to revitalize that organization; by establishing cross representation with that society on important committees; and by negotiating some sort of dicker whereby dues in engineering societies are not quite so cumulative. There is always the foolish fear present that AIEE may lose prestige or something equally intangible in supporting another body, but a strong outfit strongly in action never loses.

If the civic affairs subcommittee's suggestion is accepted as sound, then AIEE's immediate requirement is to request its Districts and Sections to undertake the formation of technical councils or local engineering societies in the political subdivisions in their area; to aid in forming a loose federation of such councils, to negotiate with the other founder societies so as to obtain their aid; and to develop a means of administering the non-technical problems that may thus arrive. Again, this approach is nontraditional; there is the ever-present fear that AIEE may become involved in "politics." It probably will and there will be many mistakes made. But at least they will be sins committed and not virtues omitted.

And finally there is the excellent report on collective bargaining. There can be no doubt that it would be a great mistake for engineers to join a union controlled by nonprofessionals. To take the positive position AIEE ought to choose a proper organization for its members and support it. Against this is the old bogey that AIEE contains employers and employees, management and labor. Every engineer—managing director, consultant, draftsman, or test man—is an employee and equally so a part of management. He and his judgment are hired. And what better repository of his interests can any engineer find than the top people of his own profession? In any event this problem as well as the other problems pertaining to the public recognition of the electrical engineer requires, in my mind, a positive AIEE position.

M. D. HOOVEN (A '24, F '44)

(Electrical engineer, electric engineering department, Public Service Electric and Gas Company, Newark, N. J.)

Value of Patents

To the Editor:

What lessons from the war period will our citizens carry with them into the postwar period? One lesson, undoubtedly, will be the need and the value of preparation. Furthermore, the people will have learned the tremendous amount of effort required to achieve a worth-while goal.

Soldiers and sailors in training sacrificed what little time was available for leisure and pleasure to study for higher ratings. They learned to convert time and effort into those higher ratings, which meant greater responsibility, greater authority and larger pay. War workers learned to convert hours of overtime into savings for the future—War Bonds, and savings accounts. The people have been taught to convert toil and labor into an asset and to convert a present sacrifice into a future benefit. They have also been taught that they can expect to enjoy these benefits when the time comes to enjoy them. So, should an inventer, also, have the confidence that he will be able to reap a reward for his efforts, when his invention is adopted by the public. When an inventer sacrifices years of time and labor, as well as money, in an effort to develop a new or better device, he hopes to be able to convert that sacrifice and effort into a valuable patent. However, there has been a tendency since about 1930 to make it more and more difficult for an inventer to enforce his patent. This has been a result of various court decisions, and attitudes of officials of certain Government departments.

DECLINE IN PATENTS

When inventers observe the trend toward depriving them of their reward, they, very properly, stop inventing. Inventing fell off considerably during the ten-year period before the entry of the United States into the war. There was a decline of 41½ per cent in patents issued during the ten-year period from 1933 to 1943. Since there is

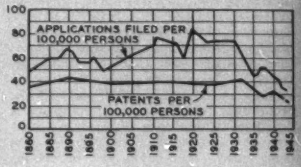

Figure 1

often a time lag of about three years between filing an application and receiving a patent, there was a close parallel between the decline in issued patents and the corresponding decline of 41 per cent in patent applications filed during the period between 1930 and 1940. The decline during this ten-year period occurred before there could be any effects from our entry into the war. Between 1930 and 1943, the decline in patent applications filed in the United States Patent Office was 54 per cent.

One reason for the patentee's difficulties which discouraged him from inventing during this period was the uncertainty whether a contribution to the art, an advancement which was considered an invention when made, would be considered an invention when the patent came up for consideration before the courts. Previously, courts had held that inventions should be judged objectively by the character of the contribution itself, and tested by the standard of long-standing want and need; by the length of time the public had to wait since the previous unsatisfactory device had been proposed; by the number of prior efforts and failures in the solution of the problem; by the novelty of mode of operation of the invention, and by the copying of the invention by the infringers and an entire industry. Later, however, some courts began to adopt the subjective standard of invention; they judged inventions, not by the character of the contribution to the art, or the extent of the advance, but rather by the manner in which the invention was made, by whom, and under what circumstances.

One of the recommendations of the National Patent Planning Commission appointed by the late President Roosevelt was the enactment by Congress of a rule requiring use of the objective standard of invention. Such a rule would go far toward restoring the value of patents, and should be enacted.

FREDERIC B. SCHRAMM (M '34)

(Patent lawyer, Cleveland, Ohio)

Applications of Thevenin's Theorem

To the Editor:

Walther Richter points out (*EE, March 1945, p. 103–05*) that this valuable theorem has found only limited application in power work because many electrical engineers are not well acquainted with it.

There is another much more recent network theorem, of particular value in communications problems, that deserves the consideration of power engineers. This is the theorem stated by Jacob Millman in his paper, "A Useful Network Theorem" (*Proceedings* of the Institute of Radio Engineers, September 1940, pages 413–17). The author discusses previous application of special cases to unbalanced polyphase networks, and shows that in general the solution of such systems can be quite easily obtained by use of a rather simple network relation.

ROBERT P. OWEN (A '44)

(Electronic engineer, Allen B. DuMont Laboratories, Inc., Passaic, N. J.)

Electrical Essays for Recreation

To the Editor:

Permit me to voice my satisfaction and enthusiasm about something new in *Electrical Engineering*, found on page 294 of the August issue, and entitled "Electrical Essays for Recreation." Material of this sort stimulates discussion and thinking about the fundamental principles of electrical engineering, and should, therefore, be highly welcome. One of the trade magazines, dealing with mechanical subjects, makes it a point to publish a puzzle of this sort every month, inviting discussions from its readers and publishing the solution in the following month's issue. I would like to see *Electrical Engineering* try a similar scheme. By offering a small prize for contributions you might entice your readers to jot down their pet puzzle (and who has not run across some baffling ones?) and to send them in to you. In a similar way, the readers might be invited to send in their solution. The best presented and clearest solution then could be published, or the reader could be awarded a prize.

As to the three puzzles presented by Harry Sohon, the first one reminds me of an incident which occurred some 25 years ago when I was working on the test floor of a large electrical firm in Europe. A young engineer finally had solved the problem of the century; a commutatorless d-c machine. The principle of that revolutionary idea is exceedingly simple. In an a-c generator, a voltage with a given polarity is induced when a north pole of the rotor passes one side of the coil while the south pole passes the other coil side. One-half cycle later, a voltage of the opposite polarity is induced because the poles passing the coil sides are now of opposite polarity. All he had to do was to see to it that only north poles would be passing one coil side and only south poles the other, which obviously was easy to accomplish by exciting the rotor with alternating current of the proper frequency. He had the idea sold to the director of the test floor and carried out the experiment by using a slip-ring induction motor, supplying 60-cycle excitation to the slip rings and driving the machine synchronously. Well, it did not work. No student would have any difficulty in recognizing what is wrong if our schools would cease to explain the law of electromagnetic induction by having a conductor "cut" magnetic lines, but would adhere strictly to the fundamental concept that a voltage is induced when the flux associated with a loop is changing. When adhering to this concept, the student would not overlook the voltage of transformation which is overlooked conveniently in both cases.

Referring to the second puzzle, the two-to-one voltage-ratio transformer, neither my associates nor myself can see any reason why the voltage linking with twice the flux will not be twice as high as the primary voltage. We agree that it might be quite difficult to build a core which will not have a terrific amount of leakage, but with leakage neglected, as postulated by the problem, there does not seem to be any reason why there should not be a voltage step-up.

Referring to the third problem, the power-factor paradox, the "nigger in the wood pile" is, of course, the statement that when the negative half wave of a ten-ampere sinusoidally varying current is suppressed, the effective value will drop to five amperes. It is true, of course, that the wattage will drop to half if current is flowing only during one-half of the time, but as the wattage is proportional to the square of the effective value of the current, the indication of an rms-type meter originally showing ten amperes will drop only to 7.07 amperes when one-half wave is going to be suppressed by the action of the rectifier.

WALTHER RICHTER (M' 37, F '42)

(Electrical engineer, engineering development department, Allis-Chalmers Manufacturing Company, West Allis, Wis.)

To the Editor:

After reading Harry Sohon's essays in the August 1945 issue of *Electrical Engineering* our readers may have many other puzzlers which they will want to submit.

I should like to offer one which has perturbed me and for which I have not yet obtained a suitable explanation.

Assume two electrons traveling adjacent to each other at high speed in a straight line. (This is the case of two electrons in the beam of a cathode-ray tube.) These electrons are moving charges and therefore constitute currents. Hence, there should be an attractive force between them since they are adjacent currents having the same direction. (This is in addition to the normal electrostatic repulsion between like charges.) However, if the observer should travel along at the same speed as the electrons, they will appear to be at rest and he will conclude that for these stationary charges there is no attractive force. Obviously, whether or not this force exists must be entirely independent of what the observer does, so that some fallacy must exist in the above reasoning.

B. LITMAN (A '42)

(Generator engineering, Westinghouse Electric Corporation, East Pittsburgh, Pa.)

To the Editor:

Harry Sohon's "Electrical Essays for Recreation" present three good examples of the result of acceptance of formulas without consideration of the underlying physics. In the first example of "D-C Generator Without Sliding Contacts" the statement appears, "Now the formula for the voltage induced in a wire cutting a magnetic field is $e = bvh$ (equation 3)." This formula applies properly to cases where the flux density is constant, but in this example where the flux density is varied, an additional voltage is induced $e = N\frac{d\phi}{dt}$. It readily can be shown that the additional voltage resulting from transformer action would make equation 4, revised,

$$e = BVh(\sin^2 \omega t - \cos^2 \omega t - \cos \omega t)$$
$$= BVh(\cos 2\,\omega t - \cos \omega t)$$

eliminating the constant term and the direct current.

In the second example, there is no error in the reasoning, and "A Two-to-One Voltage-Ratio Transformer With One-to-One Turn Ratio" is described. The transformer has two turns of the core through one of the coils, which doubles the flux linkages for that coil. The conventional transformer-turns-ratio formula ignores this unusual type of transformer, where the volts per turn are different for the two windings.

In the third example, the incorrect statement is, "The effective current is now five amperes," based on an implied formula that half-wave rectification halves the current. The effective current for the half-wave case is, of course, 7.07 amperes, making the power-factor unity.

ALFRED P. STEENSEN (A '34, M '45)

(Engineer, The Foxboro Company, Foxboro, Mass.)

Name Suggested for Insulated Conductor

To the Editor:

The wire and cable nomenclature lacks a concise term for an "insulated conductor." I suggest "icon" to fill the requirement.

The British use the word "core" for an insulated conductor. "Core" has the merit of conciseness but it is a common word of the English language, meaning the heart or center of anything, and is so used in the United States and in Canada in the wire and cable industry. That is, the core is the inner structure of a cable, about which something is added, as for example, "over the core is applied a sheath or a jacket."

The use of the term "icon" meaning an insulated conductor avoids a common ambiguity, when, for brevity, the word is used in the sense of an insulated conductor. One can use the term "icon" meaning an insulated conductor with assurance that it generally will be understood by one not already familiar with it, as the context and its evident derivation reveal its meaning.

TRACY D. WARING (A '06, M '13)
(Standard Underground Cable of Canada, Ltd., Toronto, Ontario)

Organization of the Engineering Profession

To the Editor:

I read with a great deal of interest an article by James F. Fairman of the Consolidated Edison Company (*EE, June 1945, p. 220–3*). It seems to me he has made suggestions in this article which should receive the support of many engineers, the more so if they are anxious to bring about the unification of the profession. I think you deserve a great deal of credit for publishing Mr. Fairman's article in the journal of a Founder Society. As a matter of fact, membership in the National Society of Professional Engineers should in no way interfere with membership in the Founder Societies. I trust Mr. Fairman's article will receive the general publicity which it deserves.

D. B. PRENTICE
(President, Rose Polytechnic Institute, Terre Haute, Ind.)

NEW BOOKS • • •

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Warships of the World. Edited by R. Kafka and R. L. Pepperburg, with illustrations by D. R. Merrill. Cornell Maritime Press, New York, N. Y., 1944. 1,038 pages, illustrated, 10 by 7 inches, cloth, $15. (ESL.)

This compendium of information on the navies of the world will be useful to laymen and experts alike. So far as is possible, it lists every naval vessel, with facts as to its name, size, horsepower, machinery, armament, builder, and so forth. Each class and type are pictured in photographs and line drawings. Brief accounts of the careers of many fighting ships are given. More than 7,000 ships are included in the book.

Waves and Wave Action. A bibliography of books, periodicals, and society publications appearing from 1687 through December 1943. Compiled by C. C. Lee, 1315 First North Street, Vicksburg, Miss.; revised February, 1944. 91 pages, also pages I–XVIII chronological lists, and A–L subject index; manifold copy, 10½ by 8 inches, paper, $5. (ESL.)

This is a second revision of this list which appeared originally in 1942. Nearly 800 references are listed, the majority with annotations. The arrangement is by authors, with a subject index, and a chronological one.

Aircraft Yearbook for 1944. 26th annual edition. Edited by H. Mingos. Lanciar Publishers, New York, N. Y., 1944. 727 pages, illustrated, 9 by 5½ inches, cloth, $6. (ESL.)

The new edition of this annual publication of the Aeronautical Chamber of Commerce of America reviews the events of the year, both in military and civil aviation, and the work of American manufacturers. Associations, government bureaus, and other organizations interested in aviation are listed with their officers. Statistics and records are tabulated.

Aeronautical Dictionary. By T. A. Dickinson. Thomas Y. Crowell Company, New York, N. Y., 1945. 484 pages, illustrated, 8½ by 5½ inches, cloth, $3.50. (ESL.)

This comprehensive work gives definitions of over 6,000 terms in aerodynamics, meteorology, navigation, piloting, engineering, metallurgy, design, lofting, aircraft construction, and other phases of aeronautics. More than 300 illustrations are used to clarify or amplify certain definitions. An appendix contains many tables of technical data, lists of aeronautical abbreviations, useful books and American periodicals, and other information of value.

Television Programming and Production. By Richard Hubbell. Murray Hill Books, New York 16, N. Y., 1945. 207 pages, illustrated, $3.

Provides a foundation for the techniques of television program production as an aid to broadcasters, advertising men, writers, directors, actors, designers, students, technicians, and theatrical, radio, and motion-picture people in building their television programs and projects more ably and more rapidly. Suggests practical ways in which these techniques may be improved. As an introduction to the art of television this book discusses the nature of television; the camera; video technique and theory. The last part of the book is devoted to a retrospect of television programming in England and the pioneering efforts of the British Broadcasting Corporation.

Gas Turbines and Jet Propulsion for Aircraft. By G. G. Smith. *Aerosphere*, Inc. 370 Lexington Avenue, New York, N. Y., 1944. 123 pages, illustrated, 8½ by 5½ inches, cloth, $3. (ESL.)

The history of the development of gas-turbine prime movers employing jet propulsion is presented concisely with considerable technical detail. Examples of gas-turbine units driving orthodox airscrews are included, and steam turbines are briefly reviewed. The work has been revised generally, and three new chapters have been added on turbine-compressor units, jet versus airscrew, and boundary layer control. An interesting feature is the discussion of the future possibilities of the gas-turbine power unit in the flying-wing type of aircraft.

Mechanical and Electrical Equipment for Buildings. By C. M. Gay and C. De van Fawcett. Second edition. John Wiley and Sons, Inc., New York, N. Y.; Chapman and Hall, London, England, 1945. 453 pages, illustrated, 8½ by 5½ inches, cloth, $5. (ESL.)

The coverage of this manual is indicated by the headings of the five sections: water supply, plumbing and drainage, heating and air conditioning, electric equipment, and acoustics. The purpose of the book is to acquaint architects, students, and building managers with the basic theories and applications concerned with building equipment, rather than to provide a handbook for complicated design and specifications. This edition has been rewritten considerably to conform with modern practice and the latest recommendations and provisions of the pertinent codes and standards.

Aerosphere, 1943. Edited by G. D. Angle and others. *Aerosphere*, Inc., 370 Lexington Avenue, New York, N. Y., 1944. Paged in sections, illustrated, 12 by 8½ inches, cloth, $15. (ESL.)

Aerosphere provides brief descriptions of the aircraft and aircraft engines currently being built throughout the world, together with statistical information on these industries and a buyer's guide. The arrangement is by countries, then by manufacturers. The specifications, construction, equipment, instruments, performance, and engine for each model are stated, usually with a photograph of the plane or drawing of the engine.

Electrical Essentials in Marine Service. Volume 1. By J. M. Dodds. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1945. 419 pages, illustrated, 8½ by 5½ inches, cloth, $3.

This first of three volumes gives a thorough reference-handbook treatment of all phases of marine electrical work except radio for use by marine and shipyard electricians engaged in installation, testing, repairing, and maintenance work. This volume—easy to read, easy to understand—explains the essential principles of electricity and magnetism and the characteristics of electric circuits. Alternating and direct currents are discussed together and their various uses described and compared.

PAMPHLETS • • • •

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

"Full Employment" and the "National Budget." (A Discussion of the Murray Full Employment Bill.) Citizens National Committee, Inc., Washington 9, D. C., 24 pages.

Modern Governors (For Large Hydroelectric Units Provide Centralized Control). Allis-Chalmers Manufacturing Company, Milwaukee, Wis., 24 pages.

The Use of Public Works to Sustain Construction Activity. Chamber of Commerce of the United States, Washington, D. C., 12 pages.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Ferroinductance as a Variable Electric-Circuit Element

J. D. RYDER
ASSOCIATE AIEE

IT HAS LONG been known that the inductance of iron-cored coils is not a constant, but varies with the value of current flowing, and that this is not a linear relation, owing to the shape of the magnetization curve of the iron used.

Mathematical analysis of such circuits leads to differential equations with variable coefficients which are very difficult to solve. To obtain usable results the engineer is accustomed to assume the inductance of the iron-cored reactor as constant, thereby obtaining equations with constant coefficients and an easy mathematical solution for the circuit.

However, for this analysis, in terms of complex algebra or differential equations, it is assumed that the value of the inductance is not a function of current or time. In many present-day problems this assumption cannot be supported, and a new method of analysis is needed.

Definitions

Inductance is the proportionality factor between instantaneous induced voltage and the rate of change of current in an electric circuit. That is

$$L = \frac{-e}{\frac{di}{dt}} \qquad (1)$$

is the basic defining relation for inductance.

If it is remembered that equation 1 is a relationship between instantaneous quantities, then equation 1 becomes fundamental, and other definitions such as summarized by Raner and Litscher[1] become only special cases, based on weighted averages.

Paper 45-121, recommended by the AIEE committee on basic sciences for publication in AIEE TRANSACTIONS. Manuscript submitted September 16, 1944; made available for printing May 17, 1945.

J. D. RYDER is professor of electrical engineering, Iowa State College, Ames, Iowa.

The material presented in this paper is abstracted from a dissertation presented for the doctor-of-philosophy degree at Iowa State College. The complete dissertation is on file at the Iowa State College Library, Ames, Iowa.

Ferroinductance or ferroreactance are terms used to designate the special properties of an inductance when iron is introduced into the magnetic circuit. Defining equation 1 still holds, but the value of L, the proportionality factor, is no longer a constant but is a function of i, the current.

Historical Background

Since the time the first magnetization curve was measured for a steel, there have been attempts to develop equations to fit the curve. These attempts have followed mathematical or physical paths, but it cannot be said that either method has been more successful than the other.

One of the oldest, and certainly the most famous, of the equations developed for the purpose is Frölich's equation: $B = H/(a + bH)$, which gives a satisfactory fit up to approximately the knee of the curve. Zenneck,[6] in his 1920 paper on the analysis of magnetic frequency doublers, used the relation: $B = \frac{a}{H} - s'H^2$. It should be noted that this equation cannot be used much beyond the knee of the magnetization curve because of the negative cubic term. Zenneck succeeded in obtaining an expression for ferroinductance in terms of current, but did not carry the matter further and submitted no experimental proof.

Ryan,[7] also for the analysis of magnetic frequency doublers, used the relation: $B = A \tan^{-1} ax + Cx$, which is related to that of Zenneck through the arc tangent series. Keller[11] also used a similar series. Boyajian,[14] in order to simplify the mathematics, used an approximation to the magnetization curve consisting of two straight lines, one for use below the knee, the other above. The results, while easily obtained, are not too satisfactory for a design basis.

In 1926, Gokhale,[8] using physical methods, developed an exponential form which fitted well above saturation, leaving much to be desired below the knee. Rader and Litscher[1] have used the equation: $H = K'B + K''B^{10}$, and while this fits the magnetization curves fairly well, it is impossible for use for circuit analysis, as will be discussed in the next section.

One of the earliest applications of the nonlinear voltage-current characteristics of ferroinductors was made by Zenneck[13] in 1899. This involved the use of transformers, with d-c excitation to accentuate the nonlinearity, connected to produce frequency doubling. The first report of the phenomena present in R-L-C series circuits, in which the L was ferroinductive, was made by Martienssen[9] in 1910. This is the type of circuit which we now call ferroresonant. Martienssen, while obtaining what appear to be correct qualitative results, invalidated them for quantitative use by a serious mathematical error.

More recent investigators ordinarily have used the graphic approach for a solution, but this involves the construction of a reactor before the design of the other components of the ferroresonant circuit can be completed.

A New Equation for the Magnetization Curve

The shape of the magnetization curve is obviously the cause of the phenomena observed in ferroinductive circuits. If an empirical equation for the magnetization curve is to be useful in the analysis of a-c circuits it must be a function which behaves in every way exactly as the true magnetization curve. Since actual magnetization curves are "odd" functions, and display equal and opposite effects for positive and negative currents, then the function chosen to represent the magnetization curve must likewise be an "odd" function.

The magnetization curve affects our

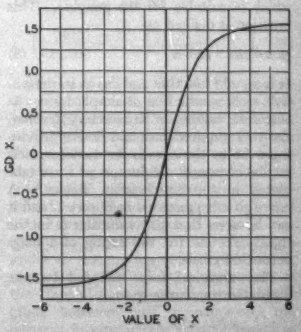

Figure 1. Variation of the gudermannian

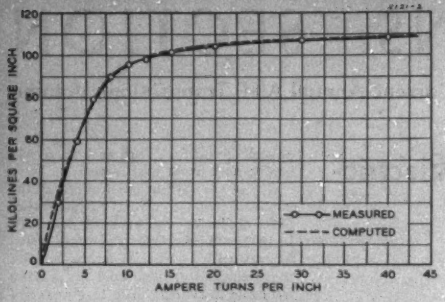

Figure 2. Measured and calculated magnetization curves for Hipersil steel

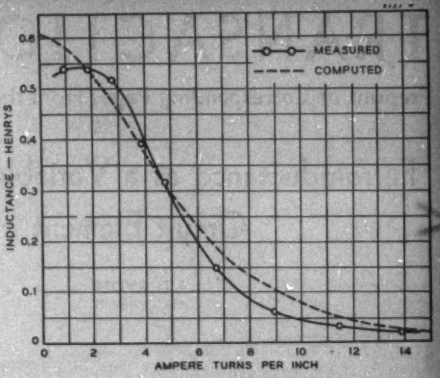

Figure 4. Measured and calculated inductance of a 156-turn reactor on Hipersil core

electric circuits indirectly, through the phenomena of flux-linkage changes or inductance. Since inductance is one of our basic circuit parameters, it is obvious that, for convenience alone, the equation chosen to represent the magnetization curve should lead to a simple expression for inductance.

Another equation for inductance, derived from equation 1 is

$$L = N\frac{d\phi}{di} \times 10^{-8} \qquad (2)$$

Thus, inductance is proportional to the slope of the magnetization curve.

It is then possible to set up two criteria which a function, to be useful as an approximation for the magnetization curve of a steel, must fulfill:

1. The function must be "odd."
2. The current derivative or slope of the function must be mathematically simple.

By applying this test to the functions used by other investigators it is found that none of the empirical relationships considered are entirely suitable for the analysis of a-c circuits. However, there exists a function, the "gudermannian",[3] which is suitable for the purpose. This function is defined as

$$gd\, x = \tan^{-1} \sinh x \qquad (3)$$

It is an odd function and has as its derivative sech x, which is of simple form. It therefore fulfills, in satisfactory fashion, the two requirements laid down, providing a fit to the curves for various steels can be obtained. Values of $gd\, x$ are tabulated in the Smithsonian Tables.[3] A curve $gd\, x$ is presented in Figure 1, and it can be seen that the variation is in the right direction for the fitting of a magnetization curve.

The empirical form adopted for the magnetization curve was

$$B = B_a gd\frac{aNi}{l} + \frac{cNi}{l} \qquad (4)$$

This equation, being a transcendental relation, does not lend itself to direct solution for the values of the constants B_a, a, and c. The method developed was that of a trial process for a, after which B_a and c were obtained directly, as outlined in Appendix III.

Results for Typical Steels

As an indication of the ability of equation 4 to approximate the magnetization curves for various commercial steels, two types were selected. The first, Hipersil, was selected as typical of modern transformer steel. As no magnetization curves were obtainable from the manufacturer, the curve was measured in the laboratory. The second steel was Nicaloi (Allegheny 4750), a high permeability alloy. The curve was available from manufacturer's data.

Using English units, the equations determined for these steels were

Hipersil:

$$B = 65{,}000\, gd\left(0.273\frac{Ni}{l}\right) + 180\frac{Ni}{l} \qquad (5)$$

Nicaloi:

$$B = 36{,}600\, gd\left(4.58\frac{Ni}{l}\right) + 6{,}200\frac{Ni}{l} \qquad (6)$$

Curves of equation 5 compared with the measured data are shown in Figure 2, with excellent agreement indicated. Equally good results have been secured for many steels other than the two described.

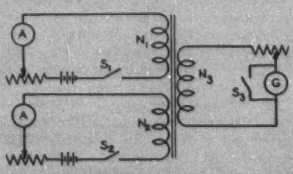

Figure 3. Circuit used for the measurement of ferroinductance

Applications of the Equation

In most modern magnetic steels the hysteresis-loop area has been much reduced and has been here neglected to simplify the mathematics. It was assumed that magnetization of the steel throughout an a-c cycle took place along the normal magnetization curve, rather than around the hysteresis loop. Leakage flux also has been neglected as it was small for the core structures used.

Normal permeability is the term obtained from the relation

$$\mu = K\frac{B}{H} \qquad (7)$$

and setting $K = 0.3125$ for English units, normal permeability can be calculated from equation 4 giving

$$\mu = 0.3125\left[\frac{B_a gd\frac{aNi}{l}}{\frac{Ni}{l}} + c\right] \qquad (8)$$

Equation 8 has been used to calculate the permeability of Hipersil and other steels with accurate results.

Differential permeability is defined as the slope of the magnetization curve, or the permeability to small changes of magnetizing force. That is

$$\mu_d = K\frac{dB}{dH} \qquad (9)$$

and, setting $K = 0.3125$ for English units,

$$\mu_d = 0.3125\left[aB_a \operatorname{sech} \frac{aNi}{l} + c\right] \qquad (10)$$

Calculations for various steels using equation 10 yield results which closely check

values of permeability obtained from the slopes of the magnetization curves.

Since

$$\phi = AB_m d\frac{aNi}{l} + \frac{cANi}{l} \tag{11}$$

$$\frac{d\phi}{di} = \frac{aAB_mN}{l}\operatorname{sech}\frac{aNi}{l} + \frac{cAN}{l} \tag{12}$$

Then, from equation 2

$$L = \frac{aAB_mN^2}{10^8 l}\operatorname{sech}\frac{aNi}{l} + \frac{cAN^2}{10^8 l} \tag{13}$$

Equation 13 gives the value, in henrys of the inductance of a ferroinductor with any value of current flowing. The first term on the right is the contribution resulting from the presence of iron, the second term is the value if the iron is removed, leaving an air core.

As the maximum value of sech x is unity and occurs for x zero, then the inductance is maximum at zero current. Actually, because of the small reverse curvature of the magnetization curve near zero, the measured inductance maximum occurs, not at, but near zero. By noting that sech ∞ equals zero, the value of inductance is seen never less than cAN^2/l. High values of current can reduce the effectiveness of the iron but never can reduce the inductance below that of the coil on an air core.

Equation 13 is a simple expression for the calculation of ferroinductance. By its use an inductor can be designed in advance of construction, to have a given inductance at a given value of current, the only data required being the constants B_m, a, and c of the steel.

Measurement of Ferroinductance

Ordinary a-c bridge methods of inductance measurement are not satisfactory. The voltage applied to the inductor varies as the bridge is balanced, changing the inductance, and a sliding balance results. If balance is obtained, knowledge of the actual current flowing through the reactor is not obtainable, and the value of inductance means nothing.

A bridge especially designed for this,[4] and including means for measuring alternating and direct currents still overlooks a fundamental point. It may give information on the inductance under the particular operating conditions, but it gives no clue to a means for determining the inductance under different conditions.

It has been necessary to develop a new method by which ferroinductance can be measured at any value of current or ampere turns. This new method is based on the relation

$$L = N\frac{d\phi}{di} \times 10^{-8} \tag{14}$$

From equation 14, it can be seen that an inductance can be measured at any value of steady current, if a differential change in current be made, the resulting differential change in flux measured, and the ratio taken and multiplied by the number of turns in the coil.

The method is based on the fact that, after demagnetization, an iron core is magnetized along the normal curve, and if the differential change is made additive, then the iron is taken further along the normal curve and the effect of a hysteresis loop is eliminated.

For accurate measurement of the differential current change it is most convenient to use a three-coil arrangement, as shown in Figure 3. The steady d-c ampere turns are applied in N_1, the differential-current change is made by closing the circuit of N_2 whose inductance is to be measured, and N_3 is for the ballistic measurement of the flux change with the galvanometer. The ampere turns of the first and second coils must be connected to aid.

The size of the differential change can be made too small for the sensitivity of the apparatus used. Values of the change used were as low as 0.001-ampere turns per inch, but it was found that values of 0.1- to 0.5-ampere turns per inch gave

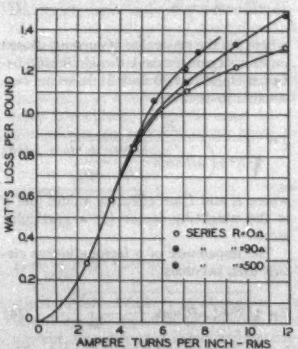

Figure 5. Wattage iron loss as a function of effective current

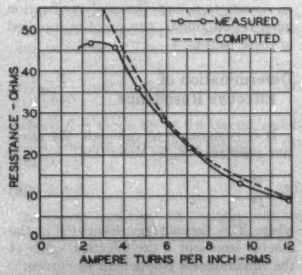

Figure 6. Effective resistance of a 156-turn reactor on Hipersil core

satisfactory results. The values of inductance so obtained were checked independently by calculations made from values of permeability obtained at the operating points. Measurements made with the Hipersil core having an area of 1.87 square inches, length of 13.2 inches, and a coil of 156 turns, are shown in Figure 4, compared with the dashed-line curve secured by computation from equation 13.

Close agreement between measured and computed values is secured over most of the range, resulting in a check of the theory and measuring method developed.

Value of Inductance for Applied Sine Electromotive Force

Consider a ferroreactor with sinusoidal electromotive force applied, neglecting the resistance of the circuit. As shown in Appendix I, an expression for the inductance as a function of time can be obtained

$$L = \frac{aAB_mN^2}{10^8 l}[J_0(G) + 2J_2(G)\cos 2\omega t + 2J_4(G)\cos 4\omega t + 2J_6(G)\cos 6\omega t + \ldots\ldots] \tag{15}$$

where

$$G = \frac{E_m 10^8}{\omega a B_m N} \tag{16}$$

This shows that, for a sine voltage, the inductance of a ferroinductor consists of a constant term plus sinusoidally varying terms in even harmonics of the applied frequency. This provides an explanation of the source of the harmonic components appearing in the current that flows through a ferroreactor.

Likewise, an expression for the current flowing can be secured in terms of the harmonic components (Appendix II)

$$i = \frac{l}{aN}\left[\left(G + \frac{G^3}{8} + \frac{5G^5}{192} + \frac{2{,}135G^7}{322{,}000} + \ldots\ldots\right)\times \sin\omega t - \left(\frac{G^3}{24} + \frac{5G^5}{384} + \frac{1{,}280G^7}{322{,}000} + \ldots\ldots\right)\times \sin 3\omega t + \left(\frac{G^5}{384} + \frac{427G^7}{322{,}000} + \ldots\ldots\right)\sin 5\omega t - \left(\frac{61G^7}{322{,}000} + \ldots\ldots\right)\sin 7\omega t + \ldots\ldots\right] \tag{17}$$

Equation 17 shows that the frequencies are odd harmonics, and alternate in algebraic sign, as is well known for this case. In Table I is presented an analysis, made with a General Radio Company wave analyzer, of an input-current wave form for sine voltage. For comparison also presented is an analysis using equation 17.

One important source of error is represented. Equation 17 was developed under an assumption of negligible circuit resistance. The effective resistance of the Hipersil core reactor was not negligible, however, and consequently the currents flowing were somewhat less than had been predicted.

Impedance of a Circuit Containing a Ferroinductor

For a series circuit of resistance, ferroinductance, and capacity, the circuit-differential equation is

$$D \operatorname{sech} \frac{aNi}{l} \frac{di}{dt} + Ri + \frac{\int i\,dt}{c} = e \qquad (18)$$

where

$$D = \frac{aAB_mN^2}{10^8 l} \qquad (19)$$

This so far has been insoluble for sinusoidal electromotive force, but if $i = I_m \times \sin \omega t$ is assumed, then the equation becomes

$$RI_m \sin \omega t + I_m\left(\omega D \operatorname{sech} \frac{aNI_m \sin \omega t}{l} - \frac{1}{\omega c}\right)\cos \omega t = e \qquad (20)$$

For equation 20 to be fulfilled, e must be nonsinusoidal. The equation is so similar in form to the conventional circuit equation

$$RI + jI\left(\omega L - \frac{1}{\omega c}\right) = E \qquad (21)$$

involving rms values of current and voltage, that it should be possible in some manner to bridge the gap between the instantaneous quantities of equation 20 and the rms quantities of equation 21.

Inductance as determined by the ferroinductance equation 13 is an instantaneous quantity, dependent on the instantaneous value of a varying current. Over a cycle of current variation the inductance changes through a considerable range of values. Its effect in the circuit will be some sort of a weighted average of the values taken during the current cycle, or a weighted function of the current or ampere turns.

The magnitude of the weighting factor will depend on the manner in which the inductance varies with the current and this is fixed by the magnetization curve. The factor in the inductance relation which reflects the shape of the magnetization curve is sech (aNi/l). Consequently, if a weighting factor is present, it will appear in the angle of the hyperbolic secant as some factor k. The effective value of inductance L_e then may be written as

$$L_e = D \operatorname{sech} \frac{kaNI}{l} \qquad (22)$$

where I is the rms value of current. Based on this argument and the similarity between equations 20 and 21 it seems reasonable to assume

$$I = \frac{E}{\sqrt{R^2 + \left(\omega D \operatorname{sech} \frac{kaNI}{l} - \frac{1}{\omega c}\right)^2}} \qquad (23)$$

where E and I are effective values and k is the weighting factor for a particular steel.

The impedance of a ferroinductive circuit then becomes

$$Z = \sqrt{R^2 + \left(\omega D \operatorname{sech} \frac{kaNI}{l} - \frac{1}{\omega c}\right)^2} \qquad (24)$$

for a particular value of current I. The resistance R includes the effective resistance of the reactor as well as other circuit resistance. Since equation 23 is an assumption, experimental verification must be obtained; the proof is supplied in these pages.

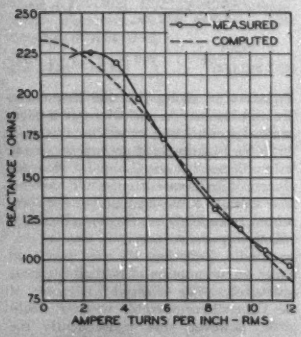

Figure 7. Measured and calculated reactance of the 156-turn reactor on Hipersil core

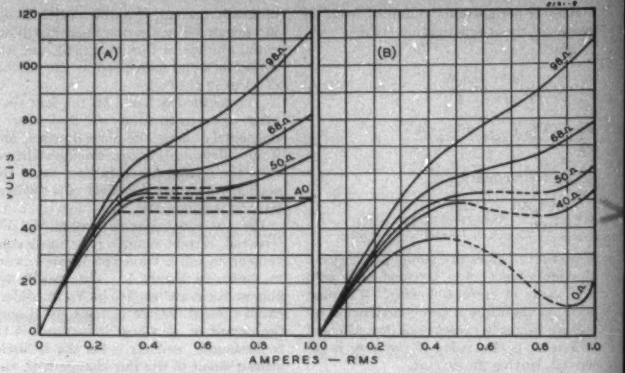

Figure 8. Voltage across a ferroresonant circuit, for various values of circuit resistance exclusive of the effective resistance

A—Measured
B—Calculated

Determination of Effective Resistance

It is customary to calculate the effective resistance R_e by definition

$$R_e = \frac{W}{I^2} \qquad (25)$$

where W is the wattage dissipated in the reactor iron and I the effective value of the fundamental component of current.

When a ferroinductor is in series with another impedance across a sinusoidal voltage, neither the current nor the voltage of the ferroinductor is sinusoidal, in general. Therefore the flux is not sinusoidal but is made up of harmonic frequencies. The total iron losses vary as some power of the frequency and are also a function of peak flux density. For convenience of measurement, the rms current, voltage, and power most readily are obtained. Consequently the relation between rms current, or ampere turns, and watts loss for such distorted wave forms would be interesting as it would reflect, not only the variation of iron losses with wave form, but also the variation of the losses with peak flux.

Data have been taken showing that the variation of losses with wave form is as much a function of rms current as of peak flux density. Evidently the change of the losses with frequency is somewhat compensated for by the accompanying change in peak factor of the current.

Figure 5 shows the losses of a reactor on Hipersil steel for various wave forms induced by the use of resistance in series with the reactor. The curves of Figure 5 can be approximated to a fair degree of accuracy by a power series of the form

$$W/\text{lb} = K_1 \frac{NI}{l} + K_2\left(\frac{NI}{l}\right)^2 + \cdots \qquad (26)$$

which then gives as an expression for R_e by use of equation 25, the following equation, in which I is in rms amperes

$$R_e/\text{lb} = \frac{K_1 N}{Il} + \frac{K_2 N^2}{l^2} + \cdots \qquad (27)$$

An experimental check of equation 27 was obtained by measuring the iron losses of the 156-turn coil on Hipersil core, com-

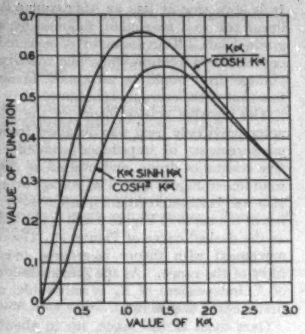

Figure 9. Values of the functions

$$\frac{k\alpha \sinh k\alpha}{\cosh^2 k\alpha} \text{ and } \frac{k\alpha}{\cosh^2 k\alpha}$$

puting the effective resistance by equation 25 and plotting as the solid curve of Figure 6. The dashed curve was computed from equation 27 using the weight of 6.9 pounds and $K_1 = 0.213$ and $K_2 = -0.00784$. The accuracy is good except over the unimportant low portion of the current values.

Calculation of Reactance

A discussion of reactance and of the design of units to give a specified value really hinges on the proof of existence of the weighting factor k of equation 22. The reactance then would be

$$X = \omega D \operatorname{sech} \frac{ka NI}{l} \tag{28}$$

The reactance can be obtained by measurement of impedance and effective resistance and using

$$X = \sqrt{Z^2 - R_e^2} \tag{29}$$

Such measurements were made on the reactor previously used and are plotted as the solid curve of Figure 7.

From Figure 7, k now can be calculated. Arbitrarily choose a point well out on the reactance curve, say at ten ampere turns per inch, at which point the reactance is 112 ohms. If a value k exists, then this point, and all other values on the curve, should be predicted by equation 28. Solving for k, a value of $k = 0.5$, is obtained. By using this value of k the calculated curve of Figure 7 was obtained, showing good agreement with the measured value. Similar good agreement has been obtained using other reactors and a wide range of steels, with values of k ranging from 0.3 to 0.5.

The experimental evidence definitely seems to establish that a factor k does exist as a weighting factor. It fully substantiates the assumptions of equation 28, and permits its use to calculate the reactance of a coil for any value of current, or to design a coil to have a particular reactance at a definite effective current value.

Table I. Harmonic Analysis of Input Current to a Reactor

	Voltage Applied = 60 Rms		Voltage Applied = 83 Rms	
	Measured	Calculated	Measured	Calculated
Total I rms	0.27	0.31	0.40	0.58
Fundamental (per cent)	100.0	100.0	100.0	100.0
Third harmonic (per cent)	7.8	7.5	20.4	17.5
Fifth harmonic (per cent)	1.8	0.7	6.7	2.7
Seventh harmonic (per cent)	0.4	0.4	3.1	2.1

The Ferroresonant Circuit

Referring to equation 23, the possibility exists that the second term under the radical may go to zero at some value of I. At this point the denominator is small and the current rises. A circuit, including a ferroreactor, in which this happens is said to be ferroresonant, because of the similarity of the properties to frequency resonance.

One of the important circuit values, useful either for design or operation, is the voltage at which the resonant current jump takes place. Since the usual definition places the reactive terms equal to zero, then at resonance

$$\omega D \operatorname{sech} \frac{ka NI}{l} = \frac{1}{\omega C} \tag{30}$$

and then

$$I_R = \frac{l}{ka N} \cosh^{-1} \omega^2 DC \tag{31}$$

where I_R is the current at resonance. It is not readily possible to measure this current, since before it is reached the current rises to a higher value. The voltage is, however, practically constant through this range and can be measured as E_R, the resonant voltage.

At resonance, as the reactance is zero, the total voltage appears across the circuit resistance. Therefore

$$E_R = \frac{Rl}{ka N} \cosh^{-1} \omega^2 DC \tag{32}$$

where R is made up of the circuit resistance plus the effective resistance of the reactor, or

$$R = R_c + R_e \tag{33}$$

Reversing equation 32 a value for the capacity required for resonance at a particular voltage E_R is

$$C = \frac{1}{\omega^2 D} \cosh \frac{ka NE_R}{Rl} \text{ farads} \tag{34}$$

Table II presents data taken to check equation 32.

Assume a series circuit using the reactor with Hipersil core and 156 turns, a capacity C of 25 microfarads, and external resistance R_x variable. Figure 8 is a plot of the voltage across the circuit, computed from equation 23, for various values of external circuit resistance R_x. The dashed portions of the curves having a negative slope cannot be realized experimentally, as the current jumps directly across. Apparently this jump starts at the point at which the negative rate of change of impedance exceeds the rate of change of current.

Measured values of voltage for various values of R_x also are plotted in Figure 8. There is a very marked agreement, especially in values of voltage at which the current jumps occur, between the measured and totally calculated values.

For values of small R_x, the jump does not occur at the same value of voltage for decreasing as for increasing voltage. The current in this region is multivalued. The amount of resistance which just permits resonance without multivalued current,

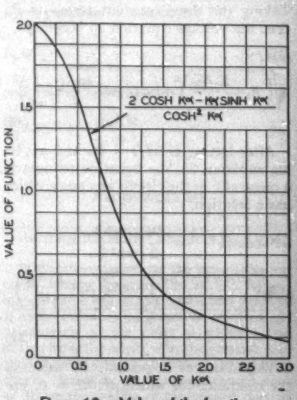

Figure 10. Value of the function

$$\frac{2 \cosh k\alpha - k\alpha \sinh k\alpha}{\cosh^2 k\alpha}$$

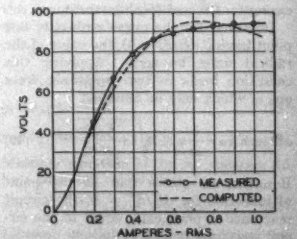

Figure 11. Variation of voltage across a pure reactance, measured and calculated

or the value producing the curve with a single point having a tangent of zero slope, is called the critical resistance R_k of the circuit. For many control applications the possibility of two current values is undesirable, so that the value of the critical resistance is of importance.

The value of R_k can be determined (see Appendix II). Briefly, the voltage can be expressed as

$$E=I\sqrt{R^2+\left(\omega D \text{ sech } \frac{k\alpha NI}{l}-\frac{1}{\omega c}\right)^2} \quad (35)$$

and the point of zero slope will have

$$\frac{dE}{dI}=0 \quad (36)$$

Before taking the derivative it is necessary to write R as a function of I, as R includes the effective resistance. From equation 27 the effective resistance may be written, and adding R_x and the copper resistance of the reactor, with w signifying the weight in pounds,

$$R=R_0+R_x+\frac{K_1Nw}{lI}+\frac{K_2N^2w}{l^2} \quad (37)$$

Taking the three constant terms as R_e, then the voltage equation 35 becomes

$$E=I\times\sqrt{\left(R_0+\frac{K_1Nw}{lI}\right)^2+\left(\omega D \text{ sech } \frac{k\alpha NI}{l}-\frac{1}{\omega c}\right)^2} \quad (38)$$

After letting $k\alpha NI/l = k\alpha$ and applying equation 36, the equation reduces to a quadratic in the circuit reactance which has a solution,

$$\omega D \text{ sech } k\alpha-\frac{1}{\omega c}=\frac{\omega Dk\alpha \sinh k\alpha}{2\cosh^2 k\alpha}\pm\frac{\sqrt{\left(\frac{\omega Dk\alpha \sinh k\alpha}{\cosh^2 k\alpha}\right)^2-4R_e\left(R_0+\frac{K_1Nw}{lI}\right)}}{2} \quad (39)$$

This indicates, in general, two values of the reactance for which $dE/dI = 0$, unless the radical is zero. The curves of Figure 8 support this. For large R_e the value of the radical is imaginary, hence no real values of reactance for $dE/dI = 0$ are possible. This is illustrated by the curves for 98- and 68-ohms resistance.

However, for the curve with only one point having $dE/dI = 0$, the value of the radical must be zero. Applying this condition leads to two equations, from one of which may be obtained

$$\omega D \text{ sech } k\alpha-\frac{1}{\omega c}=R_e\sqrt{1+\frac{K_1Nw}{lIR_e}} \quad (40)$$

Equation 40 states that at the point of inflection for $dE/dI = 0$, the circuit reactance is practically equal to the circuit resistance.

By the use of curves for the functions of $k\alpha$ involved, the value of the current at the inflection point may be found, and with further use of Figures 9 and 10 values may be obtained for substitution in

$$R_e=\frac{\omega D}{2}\frac{k\alpha \sinh k\alpha}{\cosh^2 k\alpha} \quad (41)$$

and

$$R_x=R_0-R_c-\frac{K_2N^2w}{l^2} \quad (42)$$

Values larger than this must be placed in the circuit to insure single-valued current at all times.

The value of R_k has been calculated for the circuit used for the curves of Figure 8. This results in a value of 52 ohms, which, by consideration of both measured and computed curves, is a satisfactory check.

Table II. Resonant Voltage in a Ferroresonant Circuit

C, μf	Total R, Ohms	E_R Measured, Volts	E_R Computed, Volts
16.7	78	43	45
25.0	66	54	57
41.7	53	68	64
50.0	47	70	66

Variation of Ferroreactive Voltage Drop

As mentioned, it has been customary for many years to assume ferroinductance a circuit constant, and the ferroreactive-voltage drop in a-c circuits as proportional to the current, as in

$$E_m \sin(\omega t+\theta)=\omega LI_m \sin \omega t \quad (43)$$

This is an obvious impossibility if L is considered a variable with either time or current, as actually occurs in an a-c circuit. It is now possible to determine just why and to what extent the assumption can be supported.

If

$$X=\omega D \text{ sech } k\alpha \quad (44)$$

then the ferroreactive voltage drop may be written as

$$E_L=\frac{\omega AB_mN}{10^8k}\frac{k\alpha}{\cosh k\alpha} \quad (45)$$

The ferroreactive voltage drop is seen to be a function of $k\alpha/\cosh k\alpha$. This function is plotted against $k\alpha$ in Figure 9.

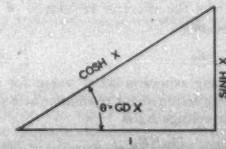

Figure 12. Property of the gudermannian

It is seen that it has an approximately linear rise to a maximum, followed by a gradual fall. If an inductor is operated on the rising portion, then the reactive voltage drop would be an almost linear function of the current, as assumed.

The reactive voltage drop for the reactor previously used was obtained from measurements of impedance and effective resistance drops, and plotted as the solid line in Figure 11. The voltage drop also was calculated from equation 45 by use of the curve of Figure 9 and is plotted as the dashed curve of Figure 11. Good agreement with theory is secured over most of the range. As the measurement of X, independent of R_e, is impossible, a better check is difficult.

Over most of the range, up to about five ampere turns per inch, the assumption of linear reactive drop is not difficult to support. This means that the linear region extends almost to the point at which the peak of the ampere-turns wave reaches the knee of the magnetization curve (see Figure 2).

Summary

This investigation was instituted in an attempt to develop methods which would make ferroinductive circuits as susceptible to analysis as circuits with constant parameters.

The work has led to the development of an accurate empirical equation for the magnetization curve of a steel. This equation has been applied in predicting the inductance of a ferroinductor at any value of current, and methods have been developed for measuring this inductance, which check the theory closely.

The equation for ferroinductance has been generalized into a relation for effective ferroreactance by an assumption, and experimental evidence has been obtained to support the validity of the assumption. Methods also were developed for calculating the effective resistance of an iron-cored reactor. Application then was made of both of these developments in calculating the impedance of circuits containing ferroreactors, and the results were again well supported by experiment.

Another application of the theory was made to the ferroresonant circuit, and simple relations for resonant voltage, capacity required, and the value of the critical resistance secured. All were checked satisfactorily by experiment.

Appendix I

Value of Inductance for Applied Sine Electromotive Force

With $e=E_m \cos \omega t$ and neglecting the resistance of the circuit, an equation for the flux present in the iron can be written

$$\phi=\frac{10^8}{N}\int e dt=-\frac{E_m10^8}{\omega N}\sin \omega t \quad (46)$$

By the expression for the magnetization curve

$$\phi = AB_n gd\frac{aNi}{l} + \frac{cANi}{l} \tag{47}$$

and ordinarily the last term on the right can be neglected as very small. Then

$$gd\frac{aNi}{l} = \frac{\phi}{AB_n} \tag{48}$$

From the properties of the gudermannian[3] a right triangle can be drawn (Figure 12) where

$$\theta = gd\frac{aNi}{l} = \frac{\phi}{AB_n} \tag{49}$$

and from which it can be seen that

$$\operatorname{sech}\frac{aNi}{l} = \cos\frac{\phi}{AB_n} \tag{50}$$

Substituting equation 46 into 50

$$\operatorname{sech}\frac{aNi}{l} = \cos\left(\frac{E_m 10^8}{\omega AB_n N}\sin\omega t\right) = \cos(G\sin\omega t) \tag{51}$$

Then equation 13 for ferroinductance, neglecting the term containing c as small, becomes

$$L = \frac{aAB_n N^2}{10^8 l}\cos(G\sin\omega t) \tag{52}$$

Now it is known that

$$\cos(x\sin r) = J_0(x) + 2J_2(x)\cos 2r + 2J_4(x)\cos 4r + \dots \tag{53}$$

where $J_0(x)$, $J_2(x)$, $J_4(x)$ . . . . . are Bessel-function coefficients which can be evaluated from tables of the function. Consequently the expression for inductance becomes

$$L = \frac{aAB_n N^2}{10^8 l}[J_0(G) + 2J_2(G)\cos 2\omega t + 2J_4(G)\cos 4\omega t + 2J_6(G)\cos 6\omega t + \dots] \tag{54}$$

Current Through a Ferroinductor, Sine Electromotive Force Applied

From equations 46 and 48 the following can be written

$$gd\frac{aNi}{l} = \frac{E_m 10^8}{\omega AB_n N}\sin\omega t \tag{55}$$

and then

$$i = \frac{l}{aN}gd^{-1}\left(\frac{E_m 10^8}{\omega AB_n N}\sin\omega t\right) = \frac{l}{aN}gd^{-1}(G\sin\omega t) \tag{56}$$

The series expression for the antigudermannian is

$$gd^{-1}\mu = \mu + \frac{\mu^3}{6} + \frac{\mu^5}{24} + \frac{61\mu^7}{5{,}040} + \dots \tag{57}$$

and equation 56 becomes

$$i = \frac{l}{aN}\left[G\sin\omega t + \frac{G^3}{6}\sin^3\omega t + \frac{G^5}{24}\sin^5\omega t + \dots\right] \tag{58}$$

By substituting for the trigonometric relations their identities in terms of multiple angles and collecting terms,

$$i = \frac{l}{aN}\left[\left(G + \frac{G^3}{8} + \frac{5G^5}{192} + \frac{2{,}135G^7}{322{,}000} + \dots\right)\times\sin\omega t - \left(\frac{G^3}{24} + \frac{5G^5}{384} + \frac{1{,}280G^7}{322{,}000} + \dots\right)\times\sin 3\omega t + \left(\frac{G^5}{384} + \frac{427G^7}{322{,}000} + \dots\right)\sin 5\omega t - \left(\frac{61G^7}{322{,}000} + \dots\right)\sin 7\omega t + \dots\right] \tag{59}$$

Appendix II

The Value of the Critical Resistance R_k

The circuit voltage, after inserting the resistance as a function of current, and setting $k\alpha NI/l$ equal to $k\alpha$, is

$$E = I\sqrt{\left(R_0 + \frac{K_1 Nw}{lI}\right)^2 + \left(\omega D\operatorname{sech} k\alpha - \frac{1}{\omega c}\right)^2} \tag{60}$$

Then applying the condition of equation 36 and collecting terms

$$0 = \frac{dE}{dI} = \left(\omega D\operatorname{sech} k\alpha - \frac{1}{\omega c}\right)^2 - \omega D\frac{k\alpha\sinh k\alpha}{\cosh^3 k\alpha}\left(\omega D\operatorname{sech} k\alpha - \frac{1}{\omega c}\right) + \left(R_0 + \frac{K_1 Nw}{lI}\right)^2 - I\left(\frac{R_0 K_1 Nw}{lI^2} + \frac{K_1^2 N^2 w^2}{l^2 I^2}\right) \tag{61}$$

The last two terms reduce to

$$R_0\left(R_0 + \frac{K_1 Nw}{lI}\right) \tag{62}$$

and equation 61 is seen to be a quadratic in the net circuit reactance and has a solution,

$$\left(\omega D\operatorname{sech} k\alpha - \frac{1}{\omega c}\right) = \frac{\omega Dk\alpha\sinh k\alpha}{\cosh^3 k\alpha} \pm \frac{\sqrt{\left(\frac{\omega Dk\alpha\sinh k\alpha}{\cosh^3 k\alpha}\right)^2 - 4R_0\left(R_0 + \frac{K_1 Nw}{lI}\right)}}{2} \tag{63}$$

For the curve for the critical resistance only one value of reactance is possible, so that the radical is zero, leading to

$$\frac{\omega Dk\alpha\sinh k\alpha}{\cosh^3 k\alpha} = 2R_0\sqrt{1 + \frac{K_1 Nw}{lIR_0}} \tag{64}$$

$$\omega D\operatorname{sech} k\alpha - \frac{1}{\omega c} = \frac{\omega D}{2}\frac{k\alpha\sinh k\alpha}{\cosh^2 k\alpha} \tag{65}$$

Substitute equation 64 into 65:

$$\omega D\operatorname{sech} k\alpha - \frac{1}{\omega c} = R_0\sqrt{1 + \frac{K_1 Nw}{lIR_0}} \tag{66}$$

Return to equation 65 and rewrite it as

$$\frac{2}{\omega^2 DC} = \frac{2\cosh k\alpha - k\alpha\sinh k\alpha}{\cosh^3 k\alpha} \tag{67}$$

The left-hand side of this equation is calculable from circuit constants. Figure 10 is a plot of the right-hand side against values of $k\alpha$. By computing the left side of equation 67, entering the curve at the value obtained for the right side, the value of $k\alpha$ may be read from the curve.

The value of I may be secured from

$$I = \frac{(k\alpha)l}{aNk} \tag{68}$$

and from equation 64 may be written

$$R_0^2 + \frac{K_1 NwR_0}{lI} - \left(\frac{\omega Dk\alpha\sinh k\alpha}{2\cosh^3 k\alpha}\right)^2 = 0 \tag{69}$$

and this may be solved as a quadratic,

$$R_0 = -\frac{K_1 Nw}{2lI} \pm \frac{\sqrt{\left(\frac{K_1 Nw}{lI}\right)^2 + \left(\frac{\omega Dk\alpha\sinh k\alpha}{\cosh^3 k\alpha}\right)^2}}{2} \tag{70}$$

Figure 9 is a plot of the function,

$$\frac{k\alpha\sinh k\alpha}{\cosh^3 k\alpha} \tag{71}$$

against $k\alpha$. From the value of $k\alpha$ obtained in the foregoing, and the value of I from equation 68, the value of R_0 may be determined. However, for most practical conditions, equation 70 reduces to

$$R_0 = \frac{\omega D}{2}\frac{k\alpha\sinh k\alpha}{\cosh^2 k\alpha} \tag{72}$$

and then R_x is found from

$$R_x = R_0 - R_c - \frac{K_2 N^2 w}{l^2} \tag{73}$$

Appendix III

Determination of the Constants B_n, a, and c

Select three points on the magnetization curve having co-ordinates x_1, y_1; x_2, y_2; x_3, y_3; where x is on the H axis and y on the B axis. Point x_1, y_1, should be selected approximately at the point at which a line drawn from the origin with the greatest possible slope is tangent to the magnetization curve. Point x_2, y_2 should be chosen near or above the middle of the curved portion of the knee, and point x_3, y_3, at a position above the knee and having x_3 equal to $2x_2$ or greater.

It is possible, if x_3 or x_2 are chosen too low, to have c become a negative number and this is undesirable as the curve will then drop at high values.

Then

$$y_1 = B_n gdax_1 + cx_1 \tag{74}$$

$$y_2 = B_n gdax_2 + cx_2 \tag{75}$$

$$y_3 = B_n gdax_3 + cx_3 \tag{76}$$

Multiply equation 74 by x_2, equation 75 by x_1 and after subtracting

$$x_2y_1 - x_1y_2 = B_n[x_2 gdax_1 - x_1 gdax_2] \tag{77}$$

Likewise multiply equation 75 by x_3 and equation 76 by x_2 and subtract

$$x_3y_2 - x_2y_3 = B_n[x_3 gdax_2 - x_2 gdax_3] \tag{78}$$

Heat-Flow Effects in a Resistance-Type Thermometer

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IT IS a well-established fact that temperature can be measured by observing the change in resistance of a given material whose resistivity is a function of temperature. This principle of temperature detection is utilized in present-day resistance-type thermometers which commonly are called "aircraft thermometer bulbs." When used in conjunction with the proper indicating instrument, the resistance-type thermometer provides an accurate system for furnishing information to the instrument panel on temperatures at remote points in an aircraft. This information is transmitted in the form of changes in electric current that are caused by variations in the electrical resistance of the temperature-sensitive element.

There are several kinds of resistance-type thermometers in use today. Probably the most common is the two-lead type used in aircraft for the measurement of engine-oil, engine-coolant, cabin-air, and free-air temperature. Figure 1 shows this type of thermometer. For these applications, the specified accuracy requirement is a resistance change of approximately 0.5 per cent throughout the temperature range of −70 degrees centigrade to +150 degrees centigrade. Although this accuracy generally is tabulated for several conditions of temperature in terms of resistance limits, it will be convenient to use per-cent accuracy or per-cent error, as the case may be, in terms of temperature change in degrees centigrade for the purpose of the discussion in this paper.

In addition to the accuracy requirement of temperature detection, this type of thermometer must have a fast response to temperature change. For a change of temperature from 100 degrees centigrade to 0 degrees centigrade in water, the thermometer must reach the 10 degree-centigrade point within eight seconds.

Since specifications for the resistance-type thermometer for aircraft applications are necessarily severe with respect to accuracy and response, a theoretical investigation of some of the factors affecting the accuracy and time of response will be of value from the viewpoint of both test and design. Although there are several factors involved in an analysis of this sort, the discussion in this paper will be limited to the effects of variations in the speed of agitation of the medium being measured on:

1. The accuracy of temperature detection for several conditions of ambient temperature affecting the screw-base head.

2. The response of the temperature-sensitive element independent of head effects.

An analysis of the first condition will be useful from a test and calibration viewpoint as it is proposed to show how errors may be introduced when ambient-temperature conditions are not controlled adequately. In the second condition, the factors affecting response as analyzed will be of interest primarily to the designer. The equations derived for response aside from emphasizing the importance of controlled conditions in test should serve as an example of a method of attack in the solution of response problems.

The fundamental equations for heat conduction between bulb and head and resulting temperature gradient expressions are completely general and may be used where two cylinders or bars of different cross sections are joined. The response expression is sufficiently general in character that it can be applied with slight modifications to other makes of re-

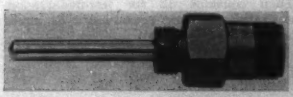

Figure 1. Typical resistance-type temperature transmitter

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Divide equation 77 by equation 78 and after clearing

$$(x_2y_1 - x_1y_1)gdax_2 = (x_1y_2 - x_1y_1)gdax_2 + (x_2y_2 - x_2y_1)gdax_1 \quad (79)$$

The coefficients of each term in equation 79 can be evaluated and the equation divided by the coefficient of the left-hand term, giving

$$gdax_2 = F_1gdax_1 + F_2gdax_1 \quad (80)$$

Values of a then are assumed and inserted in equation 80 until the equation is satisfied, thereby fixing a for the steel used. After determining a, B_a may be found from either equation 77 or 78, and c from either equation 74, 75, or 76.

Special Symbols

a = constant of a steel
A = area
B_a = constant of a steel
c = constant of a steel
$D = aAB_aN^2/10^8l$
$G = E_m10^8/aB_aN$
h = weighting constant
K_1 = iron-loss constant
K_1 = iron-loss constant
R_e = effective resistance
R_k = critical resistance
R_o = constant circuit resistance
R_c = reactor copper resistance
R_x = resistance outside reactor
w = weight
W = watts
$\alpha = ani/l$ or anI/l

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sistance-type thermometers whose construction is similar to that shown in Figures 1 and 2.

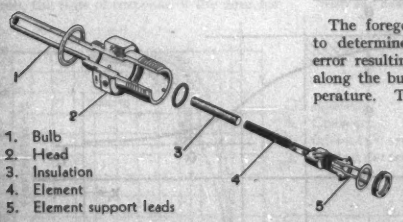
The specific problems to which these equations are applied in this paper were encountered primarily in the development of the bulb which is illustrated. The constants used in the calculations refer to developmental samples of this type of temperature bulb.

Longitudinal Temperature Distribution of Bulb and Average Temperature Error

Condition Where Base Temperature Is Constant

In the application of the bulb to a normal measurement problem, the heat flow between the threads of the screw-base head and the wall into which the head is screwed is likely to be large enough to maintain the head at substantially the temperature of the wall. For this condition the temperature gradients that exist in the outer portion of the head become unimportant with respect to the temperature distribution in the bulb. In order that the temperature distribution of the bulb for the above condition may be obtained, it becomes necessary to make the following assumptions:

1. The temperature of the head is constant.
2. The bulb cross-sectional area is constant throughout its length.
3. The temperature at any one cross section of the bulb is constant, and the flow of heat through the lead supports inside the bulb is negligible.
4. At steady state the temperature distribution in the element inside the bulb is essentially that of the bulb.
5. The heat lost from the tip can be accounted for by imagining the length of the bulb extended to such a distance that the additional surface area is equivalent to the area of the tip. For this condition no heat is lost from the end; hence, the temperature gradient becomes zero.
6. The agitated medium (gas or liquid) flows uniformly at right angles to the bulb.



1. Bulb
2. Head
3. Insulation
4. Element
5. Element support leads

Figure 2. Exploded view of a typical resistance-type temperature transmitter

Assumption 5 can be explained best by referring to Figure 3, which is a schematic sketch of the bulb and extended length and a representative temperature-distribution curve. From Figure 3 (refer to Appendix I for list of symbols employed) let

$$\theta = T_1 - \theta_x \tag{1}$$

In the foregoing expression θ_x is positive if θ_0 is a rise above T_1 and negative if θ_0 is a drop from T_1.

From assumption 5

$$\frac{\pi D_0^3}{4} = \pi D_0 \delta$$

or solving for δ

$$\delta = D_0/4 \tag{2}$$

Therefore, the effective bulb length is

$$L' = L + D_0/4 \tag{3}$$

As the solution of this type of heat-conduction problem has been worked out completely elsewhere,[1] the derivation will not be repeated here. The temperature distribution along the bulb becomes

$$\theta_x = \theta_0 \frac{\cosh (x - L')N}{\cosh L'N} \tag{4}$$

If we assume that in equation 1 θ_x is positive, as shown in Figure 3, the temperature rise then becomes

$$\theta = T_1 + \theta_0 \frac{\cosh (x - L')N}{\cosh L'N} \tag{5}$$

Once the expression for the temperature distribution is determined, it becomes useful in evaluating the average temperature error of the detector element. Referring again to Figure 3, the cross-hatched area under the curve represents the temperature error of the element because of the conduction of heat along the length of the bulb. An evaluation of this error can be determined from the average obtained by integrating equation 5.

The average temperature over the effective length of the element inside the bulb becomes

$$\theta_{av} = T_1 + \frac{\theta_0 \sinh b'N}{b'N \cosh L'N} \tag{6}$$

Finally, the per-cent error is

$$\text{Per-cent error} = 100(\theta_{av} - T_1)/\theta_0 \tag{7}$$

The foregoing equation enables one to determine the average temperature error resulting from conduction of heat along the bulb for a constant base temperature. The accuracy of results depends on how accurately the base temperature and ambient temperature of the medium are known. In practice very little error will be experienced, since the base temperature generally will be very near the value of the medium temperature.

Condition Where Temperature Gradients Exist in the Screw-Base Head

In the previous section the expression for the average temperature of the bulb is sufficient for evaluating the error for most applications, when it can be assumed reasonably that the temperature of the screw-base head is constant. However, for isolated cases where temperature gradients exist in the head, the foregoing equation will not be adequate. This condition can be realized to some extent when the bulb is supported by a material which is a relatively poor conductor of heat. It then can be assumed that negligible heat is conducted from the threads of the screw-base head into the supporting member and that the average temperature of the head is not constant. For the sake of completeness, it is proposed to record in this section the equations that may be used for evaluating the error of the bulb when ambient-temperature conditions control the average temperature of the screw-base head. No attempt will be made to derive these equations as the solution to this type of problem is described in the literature.[2]

Figure 4 shows a sketch of the bulb-head combination in which we have assumed that the head can be represented as having an average uniform cross section throughout its length. If we apply assumption 5 to the head, then

$$l' = l + D_1/4 \tag{8}$$

For the condition assumed in Figure 4

$$\theta = T_1 - \theta_x \tag{9}$$

for the bulb, and

$$\theta_1 = T_a + \theta_x' \tag{10}$$

for the head.

Once the expression for the temperature rise of the bulb (θ_x) and the head (θ_x') have been derived, equations 9 and 10 can be integrated to obtain the average temperature of the bulb and head respectively. For the bulb the average temperature becomes

$$\theta_{av} = T_1 - \frac{(T_1 - T_a)}{b'N}\left[\frac{1}{Z\dfrac{\tanh L'N}{\tanh l'N_1} + 1}\right] \times \frac{\sinh b'N}{\cosh L'N} \tag{11}$$

Similarly for the head

$$\theta_{av}' = T_a + \frac{(T_1 - T_a)}{l'N_1}\left[\frac{1}{1 + \dfrac{\tanh l'N_1}{Z \tanh L'N}}\right] \times \frac{\sinh l'N_1}{\cosh l'N_1} \tag{12}$$

Finally, using the average temperature of the bulb (equation 11), the per-cent error becomes

$$\text{Per-cent error} = 100(T_1 - \theta_{av})/(T_1 - T_a) \quad (13)$$

Heat-Transfer Coefficients

At this point it might be well to consider a few expressions for the heat-transfer coefficient of gases and liquids. An expression for the heat-transfer coefficient between a solid and a gas or a solid and a liquid is extremely complicated and does not lend itself readily to rigorous mathematical treatment. However, empirical relations have been worked out for bodies of simple geometry. The equations herein listed are for liquids or gases flowing at right angles to single cylinders[3].

COEFFICIENT FOR LIQUIDS OR GASES FLOWING AT RIGHT ANGLES TO SINGLE CYLINDERS (FORCED CONVECTION)

$$h = 0.86 k_f / D_b (D_b V \rho_f / \mu_f)^{0.43} (c_p \mu_f / k_f)^{0.3} \quad (14)$$

$$h = k_f / D_b [0.35 + 0.47 (D_b V \rho_f / \mu_f)^{0.53}] (c_p \mu_f / k_f)^{0.3} \quad (15)$$

For gases use equation 14 where $(D_b V \rho_f / \mu_f)$ varies between 0.1 and 1,000. For liquids use equation 14 when $(D_b V \rho_f / \mu_f)$ lies between 0.1 and 200 and equation 15 above 200.

COEFFICIENT FOR HEAT TRANSFER BY NATURAL CONVECTION (SINGLE CYLINDERS)

$$h_c = 0.53 k_f / D_b \left[\left(\frac{D_b^3 \rho_f^2 \beta g \Delta t}{\mu_f^2} \right) \left(\frac{c_p \mu_f}{k_f} \right) \right]^{0.25} \quad (16)$$

This expression assumes that the cylinder is placed horizontally in the liquid or gas. The writer has been unable to find a relation for vertical single cylinders. However, it is felt that for short cylinders there would be very little difference in the coefficient for the two conditions, and therefore for approximations of the coefficient equation 16 can be used for either liquids or gases. Although in some cases radiation effects may be of the same order of magnitude as convection effects, radiation will not be considered in this article.

Any consistent set of units may be used for equations 14, 15, and 16. However, in the illustrative example of computations in Appendix III, English units were used in these expressions, as these are the generally preferred units. Consequently, the heat-transfer coefficients are in English units and a conversion factor must be applied to use these coefficients in the foregoing equations for average temperature. For conversion factors refer to Appendix II and for symbols used in equations 14, 15, and 16 see Appendix I.

Effect of Agitation Velocity on Average Temperature Distribution

In the preceding paragraphs for the heat-transfer coefficient we can see that among other variables the velocity of agitation is one that might considerably affect the value of the heat-transfer coefficient. Also, the error which a change in the velocity of agitation may cause in temperature detection certainly will be to a large extent dependent upon the ambient-temperature conditions affecting the head. For example, the head may be held in an ice bath or in air and cooled by natural convection, or again in air and cooled or heated by forced convection. To show the magnitude of these effects we will assume several test conditions where we arbitrarily have selected constants from a given design for illustrative purposes only.

CONSTANT HEAD TEMPERATURE

Suppose it is required to compare the temperature measured by the resistance bulb with some other means of an oil bath where the oil-bath temperature $T_1 = 100$ degrees centigrade and the head temperature is controlled by an ice bath where $T_a = 0$ degrees centigrade. It also will be assumed that the container for the ice surrounding the head is insulated sufficiently from the oil bath that the head temperature is essentially constant at 0 degree centigrade. This condition corresponds to the required specification for test of thermal conductivity or the effect the head has on the accuracy of temperature detection. Figure 5 shows three separate plots of equation 5 of 0.5, and 2.0 feet per second, and for natural convection.

Referring again to Figure 5, the cross-hatched section represents the average temperature error over the limits of $x = 0$ to $x = b'$ where b' is the effective length of the detector element and for this particular case is equal to 4.25 centimeters. For the several conditions of agitation assumed, the errors represented by the cross-hatch sections using equations 6 and 7 are

(*a*). Natural convection per-cent error = −7.10 per cent

(*b*). V = 0.5 foot per second per-cent error = −1.39 per cent

(*c*). V = 2.0 feet per second per-cent error = −0.55 per cent

In the following table are a few average temperature errors taken from experiment on early sample production bulbs where the head has been packed in ice, the bulb inserted in oil at 100 degrees centigrade, and the oil agitation approximately 2.0 to 2.5 feet per second:

Bulb	Per-Cent Error
Number 1	−0.281
Number 2	−0.384
Number 3	−0.247
Number 4	−0.262
Number 5	−0.873
Number 6	−0.315

These errors are in good agreement with the calculated value of −0.55 per cent for an agitation of 2.0 feet per second on the same design bulb.

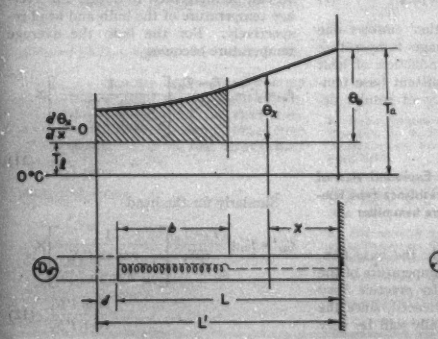


Figure 3 (left). Sketch of temperature distribution of bulb for constant base temperature

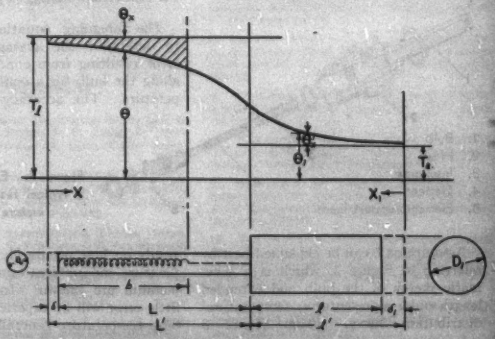


Figure 4 (right). Sketch of temperature distribution for bulb–head combination

Variable Ambient Temperature Controlling Head Temperature

In the previous section we have shown how the velocity of liquid agitation of the medium being measured affected the accuracy of temperature detection for constant head temperature. In this section we shall reverse the process and hold the bath conditions constant and determine the errors resulting from variable ambient-temperature head conditions.

Assume that the bath is oil at constant temperature $T_i = 100$ degrees centigrade and the velocity of agitation is also constant at $V = 0.5$ foot per second. For the temperature of the air, $T_a = 25$ degrees centigrade. Figure 6 shows a plot of the temperature distribution where the head is in air and cooled by natural convection and again by air flowing at right angles at a velocity of 15 feet per second. The errors as represented by the cross-hatched section for $b' = 4.25$ centimeters using equation 13 are

(a). Natural convection per-cent error = 1.09

(b). Velocity of air = 15 feet per second per-cent error = 1.32

From this analysis it is seen how variable ambient-temperature conditions controlling both the bulb and the head temperature distributions can affect materially the accuracy of temperature measurement. In an actual measurement problem in practice the ambient temperature generally will be closer to the temperature of the medium measured; hence, any errors because of conduction will tend to be negligible. However, for test purposes, in order to obtain measurable errors, the ambient temperatures often are held at extremes, and for this setup the importance of maintaining constant ambient-temperature conditions such as velocity of bath agitation, temperature, and so forth, cannot be overemphasized.

Equation for Response Time of Element

In the resistance-type temperature bulb, the time of response of the detector element is an important factor in the bulb's performance. It is desirable that the detector reach a steady-state condition in the shortest time possible. The ideal performance would be instantaneous response, but this is practically impossible to obtain as component parts of the bulb structure have certain heat capacities that introduce lagging-time characteristics. It is the designer's aim to reduce this time lag to a minimum. Consequently, from a design point of view, it would be helpful to have an expression for the response time of a typical temperature bulb that ties together all the variables of dimension and heat constants of material. Considerable testing time could be saved in the development of a design by using such an expression, as the engineer would be able to predict what would happen to the response time if changes in the variables of dimension or material were made.

Most temperature bulbs exhibit comparable component parts as viewed cross sectionally from the detector support to the outside casing. Figure 7 shows the essential components in cross section of the bulb pictured in Figure 2.

Before an analysis can be made, the following assumptions will be necessary:

1. For temperature bulbs of circular cross section, heat flow is radial to or from the detector.

2. Heat flowing along the bulb casing has negligible effect on the response time. It is recognized here that this is not a valid assumption but is made to simplify the problem. It is felt that in a properly designed bulb envelope this effect would be minimized.

3. Negligible heat flows along element support to the head.

The component parts of Figure 7 can be grouped to form bodies having definite heat capacities and resistances which impede the flow of heat. Schematically, these groups can be represented as a series-parallel circuit as shown in Figure 8. This is analogous to an electric circuit with capacitance and resistance.

The differential equation for the series-parallel heat diagram as shown in Figure 8 is

$$[s s_1 R_1 R_h D^2 + [s_1 R_h + s(R_1 + R_h)]D + 1]\theta_p = (R_1 + R_h)q + T_i - \theta_a \quad (17)$$

The solution to the differential equation 17 becomes

$$\theta_p = \frac{\theta_i - \theta_p}{m_2 - m_1}[m_2 e^{m_1 t} - m_1 e^{m_2 t}] + \theta_p \quad (18)$$

(Refer to Appendix IV for the derivation of equation 17 and solution 18 where m_1 and m_2 also are defined.)

Effect of Agitation Velocity on the Response Time

Referring to the expression for θ_p in equation 17 we see that θ_p is a sum of two temperatures, T_i which is the temperature of the medium being measured, and $(R_1 + R_h)q$, which possibly could be called the temperature of the detector element due to self-heat when current flows through it. In good designs the effect of self-heat is made very small, and if this is done the term $(R_1 + R_h)q$ can be neglected for all practical purposes. Should it ever become necessary to conduct response-time tests where it is felt the self-heat of the element is a contributing factor, then the complete expression of equation 17 should be used.

In the representative response curves of Figure 9 this self-heat term has been omitted from the calculations. These curves show the response of the element for various velocities of bath agitation. The solid lines are calculated curves assuming essentially the same arbitrary constants as previously used in the analysis of the effect of conduction, and the dotted curve is taken from experiment. The curves represent a test condition where the bulb has been heated to 100 degrees centigrade in a water bath and then suddenly immersed into a zero-degree-centi-

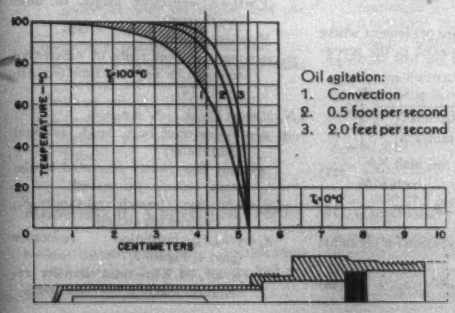


Figure 5 (left). Temperature distribution of bulb, head temperature constant

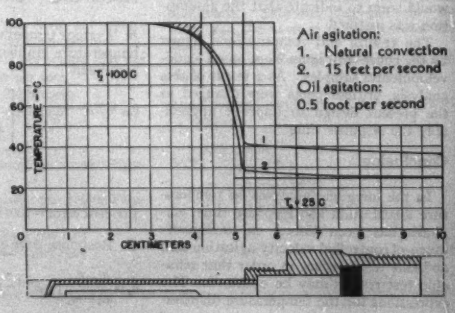


Figure 6 (right). Temperature distribution of bulb and head, bulb ambient controlled

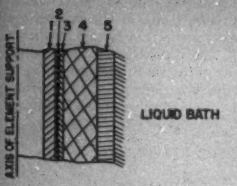


Figure 7. Sectional view of component parts for temperature bulb

1. Element support
2. Wire-wound temperature detector
3. Binder
4. Insulation
5. Wall of outside casing

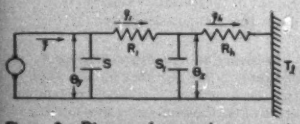


Figure 8. Diagram of grouped components for series-parallel heat flow

grade water bath. Equation 18 was used where

$\theta_i = 100$ degrees centigrade

and

$T_1 = \theta_p = 0$ degrees centigrade

Again, it is seen how a change in the velocity of agitation affects the response time. The error in reponse readily can be visualized by noticing the differences in time at any particular temperature level; for example, the ten-degree-centigrade level.

The experimental curve tends to approach the zero-degree-centigrade level slower than the calculated curves. This is possibly due to the effect of the screw-base head cooling down slower than the element. It will be recalled that the effect of the head was neglected in the calculations, but the good agreement between experimental and calculated effects would seem to indicate that the assumption was justified.

The results and computations shown by the curves of Figure 9 are based on developmental samples. As a result of this analysis, critical parts were changed in the present design to improve appreciably the response time.

Conclusion

In the foregoing analyses on temperature distribution and response time, emphasis has been placed on the importance of controlled velocity agitation and ambient temperature in order that reliable test results may be obtained. The expressions for the temperature distribu-

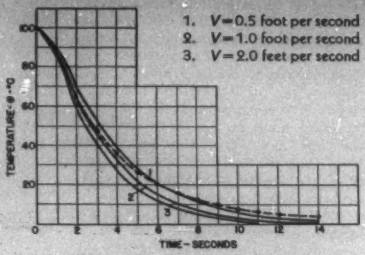


Figure 9. Response time of bulb

Response for temperature from 100 to 0 degrees centigrade in water

Solid line—Calculated
Dashed line—Experimental ($V = 0.75$ foot per second approximately)

tion of the bulb-head combination are general and can be applied to any similar problem where two bars or cylinders of different cross sections and materials are joined. Generality cannot be assigned to the response-time expression, as it must be modified and adapted to each make of temperature bulb. It was included in the discussion as an example of a method of attack in the solution of a particular response problem. The use of the response expression is limited in its accuracy when it is required to determine time-lag errors under ten per cent of the initial temperature difference. Above ten per cent of the initial temperature difference, the expression is entirely satisfactory. The condition that exists as the indicated temperature approaches more closely the final temperature is discussed extensively in an article by Noyes.[4]

For reference convenience the equations applicable to the temperature sensitive element are grouped and listed again as follows:

A. Average temperature of element for constant base temperature:

$$\theta_{av} = T_1 + \theta_b \frac{\sinh b'N}{b'N \cosh L'N} \tag{6}$$

$$\text{Per-cent error} = 100(\theta_{av} - T_a)/\theta_b \tag{7}$$

B. Average temperature of element where temperature gradients exist in the screw-base head:

$$\theta_{av} = T_1 - \frac{(T_1 - T_a)}{b'N}\left[\frac{1}{Z\dfrac{\tanh L'N}{\tanh l'N_1} + 1}\right] \times \frac{\sinh b'N}{\cosh L'N} \tag{11}$$

$$\text{Per-cent error} = 100(T_1 - \theta_{av})/(T_1 - T_a) \tag{13}$$

C. Response-time expression for element:

$$\theta_p = \frac{\theta_i - \theta_P}{m_2 - m_1}[m_2 e^{m_1 t} - m_1 e^{m_2 t}] + \theta_p \tag{18}$$

Appendix I. Symbols Used for Conduction and Response Expressions

A_s = outside surface area of bulb casing (square centimeters)

A_i = inside surface area of bulb casing (square centimeters)

A_e = outside surface area of element (square centimeters)

$A_m = \dfrac{A_i + A_s}{2}$ = mean surface area of insulation (part 4, Figure 7) (square centimeters)

A_x = mean surface area of bulb casing normal to radial flow of heat (square centimeters)

a, a_1 = average area of cross section of bulb casing, head (square centimeters)

b = length of element (centimeter)

$b' = (b + \delta)$ = effective length of element (centimeter)

c_p = thermal capacity; numerically equal to specific heat (calories per gram per degree centigrade)

D_h, D_1 = average outside diameter of bulb casing, head (centimeter)

δ, δ_1 = additional length required to make the extended surface area equal to the area at the end of the bulb, head (centimeter)

h, h_1 = heat-transfer coefficient (forced convection) between medium and bulb, head (calories per second per square centimeter per degree centigrade)

h_c, h_{c1} = heat-transfer coefficient (natural convection) between medium and bulb, head (calories per second per square centimeter per degree centigrade)

k, k_1 = thermal conductivity of bulb, head (calories per second per square centimeter per degree centigrade per centimeter)

k_m = thermal conductivity of insulation (part 4, Figure 7) (calories per second per square centimeter per degree centigrade per centimeter)

L = normal length of bulb (centimeter)

$L' = (L + \delta)$ = effective length of bulb (centimeter)

l = normal length of head (centimeter)

$l' = (l + \delta_1)$ = effective length of head (centimeter)

M = mass (grams)

m_1, m_2 = negative real roots of differential equation for response time (see Appendix IV)

N, $N_1 = \sqrt{hp/ak}$, $\sqrt{h_1 p_1/a_1 k_1}$

p, p_1 = perimeter of bulb, head (average) (centimeter)

q = heat flow (watts generated by element) (calories per second)

q_1, q_2 = heat flow through resistances R_1, R_h (calories per second)

$R_1 = y/k_m A_m$ = insulation resistance (part 4, Figure 7)

$R_h = y_1/kA_x + 1/hA_b$ = total transfer resistance made up of two items

y_1/kA_1 = the resistance of bulb casing to normal flow of heat

$1/kA_0$ = the transfer resistance to heat flow between bulb and medium

s, s_1 = total heat capacities of components (calories per degree centigrade)

$$= \sum_{1}^{n} (Mc_p)_1 \text{ (see Appendix IV)}$$

T_a = ambient temperature around head above 0 degrees centigrade (degrees centigrade)

T_1 = ambient temperature around bulb above 0 degrees centigrade (degrees centigrade)

t = time (seconds)

θ, θ_1 = temperature above 0 degrees centigrade reference for any value x, x_1 for the bulb, head (degrees centigrade)

θ_x, θ_x' = temperature change for any value x, x_1 for the bulb, head (degrees centigrade)

θ_i = initial temperature of bulb at $t=0$ (degrees centigrade)

θ_0 = temperature at junction of bulb and head above medium temperature (degrees centigrade)

$\theta_p = (R_1+R_h)q+T_1$

θ_y = temperature of detector at time t (degrees centigrade)

θ_s = temperature of grouped component s_1 (degrees centigrade)

x, x_1 = distance along bulb, head (centimeter)

y = width of space occupied by insulation (centimeter)

y_1 = thickness of bulb wall (centimeter)

$Z = akN/a_1k_1N_1$

Symbols used in heat-transfer coefficient expressions, equations 14, 15, and 16

β = coefficient of expansion

c_p = thermal capacity at constant pressure (British thermal units per pound per degree Fahrenheit)

D_0 = outside diameter of cylinder (feet)

g = acceleration due to gravity = 4.17×10^8 (feet per square hour)

h, h_c = coefficient of heat transfer, forced and natural convection respectively (British thermal units per hour per square foot per degree Fahrenheit)

k_f = thermal conductivity (British thermal units per hour per square foot per degree Fahrenheit per foot)

ρ_f = density (pounds per cubic foot)

μ_f = absolute viscosity; 2.42×centipoises (pounds per hour per foot)

V = linear velocity (feet per hour)

Δt = temperature differential between the cylinder and medium (degrees Fahrenheit)

Appendix II. Conversion Factors[5]

h = heat-transfer coefficient; (British thermal units per hour per square foot per degree Fahrenheit)

Divide h by

7,373 to get calories per second per square centimeter per degree centigrade

0.2048 to get kilogram calories per hour per square meter per degree centigrade

1,763 to get watts per square centimeter per degree centigrade

k = thermal conductivity; (British thermal units per hour per square foot per degree Fahrenheit per inch)

Divide k by

12.0 to get British thermal units per hour per square foot per degree Fahrenheit per foot

8.064 to get kilogram calories per hour per square meter per degree centigrade per meter

694.0 to get watts per square centimeter per degree centigrade per centimeter

2,903.0 to get calories per second per square centimeter per degree centigrade per centimeter

Appendix III. Example of Computations

For the purpose of illustrating how the conduction equations can be applied, one example of the computations will be given. The per-cent error will be computed from constants of a given design for one condition of medium agitation. For this condition it will be assumed that the head is placed in water at 0 degrees centigrade and that heat is transferred from the head to the water by natural convection only. The temperature of the medium being measured will be held constant at 100 degree centigrade and the medium will be a light grade of machine oil.

Constants (see Appendix I for list of symbols)

$T_1 = 100$ degrees centigrade

$T_a = 0$ degrees centigrade

$D_0 = 0.711$ centimeter $= 0.0233$ foot

$D_1 = 1.53$ centimeter $= 0.0502$ foot

$a = 0.139$ square centimeter

$a_1 = 1.84$ square centimeters

$p = 2.24$ centimeters

$p_1 = 4.81$ centimeters

$k = 0.036$ calorie per second per square centimeter per degree centigrade per centimeter

$k_1 = 0.160$ calorie per second per square centimeter per degree centigrade per centimeter

$k_f = 5.68\times10^{-2}$ Btu per hour per square foot per degree Fahrenheit per foot

$k_\Lambda = 0.29$ Btu per hour per square foot per degree Fahrenheit per foot

$\rho_f = 57.40$ pounds per cubic foot

$\rho_\Lambda = 62.40$ pounds per cubic foot

$\beta = 9.5\times10^{-4}$

$\beta_1 = 2.1\times10^{-4}$

$c_p = 0.51$ Btu per pound per degree Fahrenheit

$c_{p1} = 1.0087$ Btu per pound per degree Fahrenheit

$\mu_f = 43.5$ pounds per hour per foot

$\mu_\Lambda = 4.33$ pounds per hour per foot

$L = 5.08$ centimeters

$l = 4.13$ centimeters

Let V = one foot per second (velocity of agitated oil bath)

From equations 3 and 8

$L' = 5.26$ centimeters

$l' = 4.51$ centimeters

In determining which equation to use for the heat-transfer coefficient for the agitated oil bath, we must evaluate the expression $(D_0V\rho_f/\mu_f)$, remembering that all the variables in all the expressions for the heat-transfer coefficients are in English units and V is in feet per hour.

$$\left(\frac{D_0V\rho_f}{\mu_f}\right) = \frac{0.0233\times3{,}600\times1\times57.40}{43.5} = 111$$

This is less than 200; therefore, we must use equation 14.

$$h = \frac{0.86k_f}{D_0}\left(\frac{D_0V\rho_f}{\mu_f}\right)^{0.43}(c_p\mu_f/k_f)^{0.3} \qquad (14)$$

$$h = \frac{0.86\times5.68\times10^{-2}}{2.33\times10^{-2}}\times\left(\frac{0.0233\times3{,}600\times57.40}{43.5}\right)^{0.43}\left(\frac{0.51\times43.5}{5.68\times10^{-2}}\right)^{0.3}$$

$h = 2.1(111)^{0.43}(390)^{0.3} = 95$ Btu per hour per square foot per degree Fahrenheit or in the metric system (see Appendix II for conversion factors)

$$h = \frac{95}{7{,}373} = 0.013 \text{ calorie per second per square centimeter per degree centigrade}$$

Now

$$N = \sqrt{\frac{kp}{ak}} = \sqrt{\frac{0.013\times2.24}{0.139\times0.036}} = 2.41$$

$$L'N = 5.26\times2.41 = 12.68$$

Before we can proceed any further with calculations on the bulb, we now will have to evaluate the heat-transfer coefficient for the head. For this determination we must use equation 16 for natural convection as the water bath was assumed unagitated.

$$h_{c1} = \frac{0.53k_\Lambda}{D_1}\left[\left(\frac{D_1{}^3\rho_\Lambda{}^3\beta_1 g\,\Delta t}{\mu_{f1}{}^2}\right)\left(\frac{c_{p1}\mu_\Lambda}{k_{f1}}\right)\right]^{0.25} \qquad (16)$$

It will be noticed that this expression involves the term Δt which is the temperature difference between the water and the head. Therefore, it becomes necessary by trial and error to assign values to Δt until the value assigned is approximately equal to the temperature difference between the ice water and the average temperature of the head.

Let us assume for the first approximation that

$\Delta t = 4$ degrees centigrade $= 7.2$ degrees Fahrenheit

$$h_{c1} = \frac{0.53\times0.29}{0.0502}\times\left[\left(\frac{0.0502^3\times62.4^3\times2.1\times10^{-4}\times4.17\times10^8\times7.2}{4.33^2}\right)\times\left(\frac{1.0087\times4.33}{0.29}\right)\right]^{0.25}$$

$h_m = 3.07[(16.5\times10^3)(15.05)]^{0.33}$

$= 3.07\times22.3 = 68.5$ Btu per hour per square foot per degree Fahrenheit

or

$h_{cs} = \frac{68.5}{7,373} = 0.0093$ calorie per second per square centimeter per degree centigrade

Now

$N_1 = \sqrt{\frac{h_{cs}\rho_1}{a_1 k_1}} = \sqrt{\frac{0.0093\times4.81}{1.84\times0.160}} = 0.389$

and

$l'N_1 = 4.51\times0.389 = 1.76$

$Z = \frac{akN}{a_1 k_1 N_1} = \frac{0.139\times0.036\times2.41}{1.84\times0.160\times0.389}$

$= 10.54\times10^{-2}$

We can now calculate the average temperature of the head from equation 12.

$$\theta_{av}' = T_a + \frac{(T_1 - T_a)}{l'N_1}\times\left[\frac{1}{1+\frac{\tanh l'N_1}{Z\tanh L'N}}\right]\frac{\sinh l'N_1}{\cosh l'N_1} \quad (12)$$

$\tanh L'N = 1$

$\tanh l'N_1 = 0.943$

$\sinh l'N_1 = 2.820$

$\cosh l'N_1 = 2.992$

Therefore

$$\theta_{av}' = \frac{100}{1.76}\left[\frac{1}{1+\frac{0.943}{10.54\times10^{-2}}}\right]\frac{2.820}{2.992}$$

$\theta_{av}' = 56.8\left(\frac{1}{9.95}\right)\times0.943 = 5.4$ degrees centigrade

Now, since $T_a = 0$ degree centigrade, this value represents the temperature change between the ice water and the head. Comparing this value of 5.4 degrees centigrade with the originally assumed value of $\Delta t = 4$ degrees centigrade, we see that we must assume another value and go through the same procedure as previously outlined until the two values check within reasonable limits. The value of Δt obtained after two more trials is

$\Delta t = 4.9$ degrees centigrade

If we use this value, then

$h_{cs} = 0.00979$ calorie per second per square centimeter per degree centigrade

$N_1 = 0.399$

$l'N_1 = 1.80$

$Z' = 10.28\times10^{-2}$

Having once found the above variables for the correct Δt, we now can proceed with the calculation of the average temperature of the bulb and the consequent error.

From equation 11 we have

$$\theta_{av} = T_1 - \frac{(T_1 - T_a)}{b'N}\times\left[\frac{1}{\frac{Z\tanh L'N}{\tanh l'N_1}+1}\right]\frac{\sinh b'N}{\cosh L'N} \quad (11)$$

which is the expression for the average temperature distribution between the limits $x = 0$, $x = b'$ for the element inside the bulb. (Refer to Figure 4)

$b' = 4.25$ centimeters

$b'N = 4.25\times2.41 = 10.25$

$\tanh L'N = 1$

$\tanh l'N_1 = 0.947$

$\sinh b'N = {}^1/_2 e^{b'N} = 1.41\times10^4$

$\cosh L'N = {}^1/_2 e^{L'N} = 15.9\times10^4$

For $(L'N)$ or any other value of the hyperbolic radian > 6.0,

$\sinh L'N = \cosh L'N = {}^1/_2 e^{L'N}$

Therefore,

$$\theta_{av} = 100 - \frac{(100-0)}{10.25}\times\left[\frac{1}{\frac{10.28\times10^{-2}}{0.947}+1}\right]\times\frac{1.41\times10^4}{15.9\times10^4}$$

$\theta_{av} = 100 - 9.75\left(\frac{1}{1.109}\right)\times0.0887 = 100 - 0.78$

$\theta_{av} = 99.22$ degrees centigrade

Finally from equation 13

$$\text{Per-cent error} = \frac{(T_1 - \theta_{av})}{T_1 - T_a}\times100 \quad (13)$$

$$\text{Per-cent error} = \frac{(100-99.22)}{100}\times100 = 0.78$$

Appendix IV. Derivation of Equation for Response Time

Referring to Figure 7, the summation of the heat capacities of parts 1, 2, 3, and one half of part 4 can be expressed mathematically as follows:

$$s = (Mc_p)_1 + (Mc_p)_2 + (Mc_p)_3 + {}^1/_2(Mc_p)_4 \quad (19)$$

where, for example, $(Mc_p)_1$ is the heat capacity of part 1 or its mass M times its specific heat c_p.

Similarly

$$s_1 = {}^1/_2(Mc_p)_4 + (Mc_p)_5 \quad (20)$$

Now referring to Figure 8, the heat gained in calories per second by the body having a heat capacity s is

$$s\frac{d\theta_y}{dt} = q - q_1$$

or, solving for $\frac{d\theta_y}{dt}$,

$$\frac{d\theta_y}{dt} = \frac{q - q_1}{s} \quad (21)$$

Similarly

$$\frac{d\theta_s}{dt} = \frac{q_1 - q_h}{s_1} \quad (22)$$

Now the flow of heat from one body to another is equal to the difference in temperature of the two bodies divided by the resistance of the path; therefore

$$q_1 = \frac{(\theta_y - \theta_s)}{R_1} \quad (23)$$

and

$$q_h = \frac{(\theta_s - T_1)}{R_h} \quad (24)$$

Substituting equations 23 and 24 in 21 and 22 and simplifying

$$\frac{d\theta_y}{dt} = 1/sR_1[q R_1 - (\theta_y - \theta_s)] \quad (25)$$

and

$$\frac{d\theta_s}{dt} = 1/s_1R_1R_h[R_h\theta_y - (R_1+R_h)\theta_s + R_1T_1] \quad (26)$$

Making use of the differential operator $D = \frac{d}{dt}$ equations 25 and 26 can be written

$$(D + 1/sR_1)\theta_y - \theta_s/sR_1 - q/s = 0 \quad (27)$$

$$[D + (R_1+R_h)/s_1R_1R_h]\theta_s - \theta_y/s_1R_1 - T_1/s_1R_h = 0 \quad (28)$$

If equation 28 is solved for θ_s and substituted in equation 27 and remembering that $Dq = 0$, that is, for any one condition the flow of heat is constant, thus making the rate of change of heat flow equal to zero, one obtains after simplifying, the differential equation for the response time

$$[ss_1R_1R_hD^2 + [s_1R_h + s(R_1+R_h)]D + 1]\theta_y = (R_1+R_h)q + T_1 = \theta_y \quad (17)$$

Now the solution of the differential equation

$$(\alpha D^2 + \eta D + 1)\theta_y = 0 \quad (29)$$

will be of the form

$$\theta_y = c_1e^{m_1t} + c_2e^{m_2t} \quad (30)$$

where c_1 and c_2 are constants to be evaluated for the boundary conditions and m_1 and m_2 are roots of the auxiliary equation

$$\alpha m^2 + \eta m + 1 = 0 \quad (31)$$

Also

$$\alpha = ss_1R_1R_h \quad (32)$$

$$\eta = s_1R_h + s(R_1+R_h) \quad (33)$$

The auxiliary equation yields two negative real roots,

$$m_1 = \frac{-\eta + \sqrt{\eta^2 - 4\alpha}}{2\alpha} \quad (34)$$

and

$$m_2 = \frac{-\eta - \sqrt{\eta^2 - 4\alpha}}{2\alpha} \quad (35)$$

By actual substitution for the quantities under the radical sign it can be shown that m_1 and m_2 are negative real roots.

A particular solution of the differential equation 17 will be

$$\theta_y = (R_1+R_h)q + T_1 \quad (36)$$

or

$$\theta_y = \theta_p \quad (37)$$

Sag and Tension Calculations for Cable and Wire Spans Using Catenary Formulas

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IT IS generally agreed that, in order to obtain accurate solutions of sag and tension problems involved in stringing electric power line conductors, it is necessary to use catenary formulas. The basic formulas are, of course, well known. In order to utilize them, however, a great amount of laborious calculating is required. Certain short cuts in these calculations have been evolved, notably by James S. Martin whose published tables and method have proved of great help to engineers in simplifying sag calculations.

In connection with the design and construction of transmission lines in the mountainous Appalachian region the writers have evolved a method of making mathematically exact sag and tension calculations based on catenary formulas which is quite different from the Martin method, and which eliminates the trial-and-error assumptions involved in a portion of the Martin method. The working formulas used by the writers require only simple arithmetical calculations which can be handled by clerical personnel usually available in the engineering office. The calculations are not laborious, and can be easily checked.

The writers' method not only develops the sags, tensions, and conductor lengths for the various final and initial conditions of the design span (basic or ruling span), but also similar data for span lengths other than the ruling span.

The procedure outlined is applicable to any cable or wire whose modulus of elasticity and coefficient of expansion are uniform throughout the cross section, such as is the case with copper, copper-coated-steel, or steel cables. Sag and tension problems for composite cables such as aluminum cables steel reinforced, are usually solved by graphic methods based on stress-strain curves developed from laboratory tests on the particular cable under consideration.

The writers' method does, however, develop previously unpublished relationships between sags, tensions, and cable lengths which are applicable not only to copper, copper-coated-steel, and steel cables, but also to problems involving composite cables, which information cannot be secured by graphic methods alone.

The following text gives the basic catenary formulas, the derivations thereof, and an explanation of the procedure followed in actual sag calculations.

The basic formulas of the catenary are shown on Figure 1. The nomenclature used in this figure is as follows:

X and Y = Cartesian co-ordinates of any point in the catenary curve, designated point B
Z = length of catenary from the vertex A to point B
S = the deflection of the vertex A below any point B which may be under consideration
V = vertical distance from the axis of abscissas of the catenary to the vertex A
A = vertex of the catenary curve
e = base of the Naperian or natural system of logarithms equals 2.71828

These formulas are well known and need no proof of derivation. Formula A determines the shape of the catenary curve which shape depends on the V function. Formula B determines the length of the curve which depends on the same V function. It will be shown later that the value of V depends on the cable tension at the span vertex, and the value of Y depends on the total tension in the cable. The sag is $Y-V$ (formula C) which can be expressed in terms of the V value and span length (formula D).

Referring to Figure 1 note that point B is a cable support, X the horizontal distance from the vertex (low point of sag) to support, and Z the cable length from vertex to support. S is the sag of the cable below its support, or the span sag in problems with equal elevation supports.

Unit Values of Catenary Functions

In catenary spans the values of V, Y, S, and Z bear definite relationships to each other expressed by the basic formulas, A, B, and C. When these formulas are divided by X, unit value formulas result as follows:

$$Y/X = V/X \cosh X/V$$
$$Z/X = V/X \sinh X/V$$
$$S/X = (Y/X)-(V/X)$$

Related unit values of V/X, Y/X, S/X, and Z/X are tabulated in Table I, which values can be applied to any length span, or any type cable. When V, Y, Z, or S is known for any span the other values are quickly determined by interpolation. These table values are derived from ten-place hyperbolic sine and cosine tables and these values have the same accuracy as the sinh and cosh tables. Table I values

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where

$$\theta_y = (R_1+R_2)q+T_1 \quad (38)$$

therefore the general solution to equation 17 is

$$\theta_y = c_1e^{m_1t}+c_2e^{+m_2t}+\theta_p \quad (39)$$

The boundary conditions that must be satisfied are

$$\theta_y = \theta_1$$

and

$$\frac{d\theta_y}{dt}=0$$

when $t=0$,

and

$$\theta_y = \theta_p$$

when $t=\infty$.

If these boundary conditions are substituted in equation 39, the value of c_1 and c_2 can be determined

$$c_1 = (\theta_1-\theta_p)m_2/(m_2-m_1) \quad (40)$$

$$c_2 = -(\theta_1-\theta_p)m_1/(m_2-m_1) \quad (41)$$

Finally putting c_1 and c_2 back into equation 39 the solution to the differential equation 17 becomes

$$\theta_y = \frac{\theta_1-\theta_p}{m_2-m_1}[m_2e^{m_1t}-m_1e^{m_2t}]+\theta_p \quad (18)$$

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eliminate laborious calculations and provide speed and accuracy in solving sag and tension problems.

Additional Formulas and Nomenclature

The following text explains the additional formulas, derived from the basic catenary characteristics, which are used in this procedure.

Let the following nomenclature be used:

l = horizontal span length between supports
L = catenary arc length of the span
T = tension (total) in cable
F = horizontal longitudinal component of tension in cable. It will be seen from formulas given hereinafter that F equals T at the span vertex
H = horizontal loading per foot of cable due to wind pressure on cable (cable only or cable with ice loading)
W = vertical loading per foot of cable due to weight of cable (cable only or cable with ice loading)
R = resultant loading per foot of cable due to horizontal and vertical loading
ZE = elongation of Z (not permanent stretch) due to loading
ZT = change in length of Z due to temperature change
a = cross-section area of cable
M = modulus of elasticity of cable
C = coefficient of linear expansion per degree temperature change
d = temperature change in degrees
lu = unit permanent set of cable due to loading
lt = total permanent set of cable due to loading

The additional formulas are set out and explained in the following:

$l = 2X$ (when both supports are at the same elevation) (E)

Refer to appendix for the relationship of l to x where span supports are at unequal elevations.

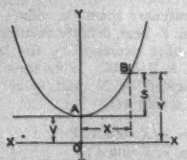


Figure 1. The catenary and its basic formulas

$$Y = (V/2)(\epsilon^{X/V} + \epsilon^{-X/V}) \quad (AA)$$

$$Y = V \cosh X/V \quad (A)$$

$$Z = (V/2)(\epsilon^{X/V} - \epsilon^{-X/V}) \quad (BB)$$

$$Z = V \sinh X/V \quad (B)$$

$$S = Y - V \quad (C)$$

$$S = V(\cosh X/V - 1) \quad (D)$$

CATENARY DATA SHEET—NO. 1

CABLE 7/0 B.H.D. 7-Strand Copper BASIC SPAN 2000 Ft.

LOADING AND TEMPERATURE RANGE	COORDINATE Y	FUNCTION V	½ LENGTH Z	TENSION T	HOR. LONG. TEN. F	SAG S
Final CODE	z(1)C	3	4(2)	1	1A(3)H	5(2-3)
0° ICE-8LB WIND	2620.486	2869.996	1028.957	3556.05	3270.36	210.50
CODE	12(6)	11(6)	6(2,3,4)I			
0°-UNSTRESSED	2697.560	2949.401	1027.007			
CODE	14(7)	13(7)	7(4)J			
32° UNSTRESSED	2685.002	2936.630	1027.316			
CODE	16(8)	15(8)	8(6)J			
60°-UNSTRESSED	2677.020	2928.663	1027.586			
CODE	18(9)	17(9)	9(6)J			
90°-UNSTRESSED	2662.234	2913.777	1027.876			
CODE	20(10)	19(10)	10(6)J			
120°-UNSTRESSED	2650.448	2902.896	1027.146			
Final CODE	27(21)	28(24)	21(6,11,12)I	41(27)G	41A(26)H	22(27-26)
0°-CABLE ONLY	2472.694	2461.197	1021.648	1103.82	1018.95	205.98
Final CODE	30(22)	29(22)	22(9,13,14)I	42(30)G	42A(29)H	31(30-29)
32°-CABLE ONLY	2460.243	2453.594	1027.935	1091.65	1013.34	206.64
Final CODE	33(23)	32(23)	23(8,15,16)I	43(33)G	43A(32)H	34(33-32)
60°-CABLE ONLY	2649.391	2441.735	1028.182	1089.20	1008.44	207.66
Final CODE	36(24)	35(24)	24(9,17,18)I	44(36)G	44A(35)H	37(36-35)
90°-CABLE ONLY	2438.396	2429.651	1028.448	1089.65	1003.45	208.73
Final CODE	39(25)	38(25)	25(10,19,20)I	45(39)G	45A(38)H	40(39-38)
120°-CABLE ONLY	2627.647	2417.814	1028.767	1085.20	998.56	209.78
Initial CODE	52(46)	51(46)	46(21)K	68(52)G		53(52-51)
0°-STRINGING	2689.777	2485.914	1027.198	1110.89		203.88
Initial CODE	55(47)	54(47)	47(22)K	69(55)G		56(55-54)
32°-STRINGING	2677.341	2472.236	1027.569	1105.75		205.05
Initial CODE	58(48)	57(48)	48(23)K	68(58)G		59(58-57)
60°-STRINGING	2666.542	2460.481	1027.770	1101.28		206.06
Initial CODE	61(59)	60(59)	49(24)K	69(61)G		62(61-60)
90°-STRINGING	2651.837	2447.689	1028.058	1096.75		207.15
Initial CODE	64(60)	63(60)	50(25)K	70(64)G		65(64-63)
120°-STRINGING	2643.457	2435.228	1028.345	1091.75		208.23

CABLE CHARACTERISTICS		LOADING - POUNDS PER FOOT OF CABLE	
ULTIMATE STRENGTH, LBS.	5927	RESULTANT, 8 LB WIND ½" ICE	1.357
CROSS SECTION, SQ. INCHES	0.1045	VERTICAL CABLE ONLY	0.413
MODULUS OF ELASTICITY	17.1×10⁶	VERTICAL CABLE WITH ½" ICE	0.919
CO-EFF. OF LINEAR EXPANSION	9.91×10⁻⁶	HORIZONTAL 8 LB WIND ½" ICE	0.940

Figure 2

$L = 2Z$ (supports at the same elevation) (F)

Refer to appendix for relationship of L to Z where span supports are at unequal elevations.

$$T = YR \quad (G)$$

The tension in a cable at any point is equal to the Y co-ordinate at that point times the per foot loading of the cable. In problems without wind pressure, $T = YW$.

This formula is due to a certain peculiarity of the catenary. The tension in a cable at any point in a span is equal to the loading on a piece of cable of the length of the function Y at that point in the span. If the cable, assumed to be perfectly flexible, were hung in a frictionless pulley at any point in the span with a length of cable hanging down just sufficient to reach the axis of the Y co-ordinate, the curve of the catenary would be undisturbed. (Reference: Martin's tables.)

The formula shows that the Y function used in the catenary formulas is proportional to the total tension in the cable.

At the low point of sag (vertex) $Y = V$ (refer to formula A) and $T = F$ so that substitutions in formula just given produces the one which follows.

$$F = VR \quad (H)$$

The horizontal longitudinal component of tension in a cable is equal to the V function times the per-foot cable loading. In problems without wind pressure, $F = VW$.

This formula shows that the V function used in the catenary function is proportional to the tension at the cable vertex.

Since $Y = V + S$ (from formula C) formula G may be written:

$$T = (V + S)R$$

Therefore:

$$T = F + SR$$

This indicates that the tension in a cable at a support is equal to the horizontal longitudinal component of tension plus the product of the sag times the per foot cable loading. This relationship holds with spans which have supports at the same or at unequal elevations provided S is taken as the deflection of the vertex below the support in question. This formula provides a quick determination of tension increase at sup-

CATENARY DATA SHEET—NO. 2

CABLE 2/0 B.H.D. Copper, 7-Strand BASIC SPAN 2000 Ft

LOADING AND TEMPERATURE FAHR.	SPAN LENGTHS 200	400	800	1200	1600	2000
0°-½ ICE-8LB WIND	2.09	8.33	33.30	75.09	134.02	210.50
0°-CABLE ONLY	2.03	8.12	32.52	73.35	130.87	205.48
32°-CABLE ONLY	2.05	8.17	32.70	73.76	131.61	206.64
60°-CABLE ONLY	2.06	8.21	32.87	74.12	132.25	207.66
90°-CABLE ONLY	2.07	8.26	33.03	74.49	132.91	208.78
120°-CABLE ONLY	2.08	8.30	33.19	74.85	133.57	209.79
0°-STRINGING	2.01	8.06	32.26	72.78	129.86	203.88
32°-STRINGING	2.03	8.10	32.45	73.19	130.60	205.05
60°-STRINGING	2.04	8.15	32.61	73.55	131.24	206.06
90°-STRINGING	2.05	8.19	32.79	73.94	131.93	207.15
120°-STRINGING	2.07	8.24	32.96	74.32	132.61	208.23

LOADING AND TEMPERATURE FAHR.	SPAN LENGTHS 2200	2400			3000	
0°-½ ICE-8LB WIND	255.46	305.90			482.10	
0°-CABLE ONLY	249.34	294.66			470.23	
32°-CABLE ONLY	250.75	296.86			472.89	
60°-CABLE ONLY	252.00	300.87			475.45	
90°-CABLE ONLY	253.21	302.44			477.95	
120°-CABLE ONLY	254.61	303.98			480.42	
0°-STRINGING	247.39	285.33			447.48	
32°-STRINGING	248.81	287.02			450.30	
60°-STRINGING	250.04	288.50			452.67	
90°-STRINGING	251.37	300.10			474.21	
120°-STRINGING	252.71	301.72			476.80	

ports over tension at the vertex. In long-span construction this increase is an appreciable item.

Effect in Change of Loading

Elongation of Z (not permanent stretch) due to cable loading is determined by formula I.

$$ZE=(R/2aM)(XV+YZ) \qquad (I)$$

This formula is ably developed in the Martin method of sag and tension calculations Under conditions of no wind W replaced R in this formula.

Note the following variations in formula I.

$$ZE=(RVX+RYZ)/2aM$$

Therefore:

$$ZE=(FX+TZ)/2aM \qquad (I\text{-}1)$$

Effect of Temperature Change

Changes in cable length due to temperature changes are found by using formula J.

$$Z1=CdZ \qquad (J)$$

The change in conductor length due to variation in temperature depends on the original length, the coefficient of expansion, and the degrees temperature variation.

Figure 3

Solve for sag by using Table I, remembering that the V in V/X is the same V value occurring for the basic span under similar loading conditions. The related S/X value multiplied by one-half the span produces the sag value

Determination of Permanent Stretch

The following procedure is suggested for securing the permanent set (in Z) due to loading previously unstressed cables.

First determine loaded stress in cable as follows:

Stress (at support) $=T/a$
Stress (at vertex) $=F/a$
Stress (span average) $=(T+F)/2a$

This value is a close value to use with permanent-set charts for the cable under consideration From the chart determine the unit permanent set, ku, caused by design loading, $(T+F)/2a$, and the unit permanent set, ku, for the probable stringing stress. The difference between these k values will be the net unit permanent set to be used in calculating stringing sags and tensions.

$$KT=KuZ \qquad (K)$$

Problem Solution Procedure

The authors recently designed and built an 88-kv transmission line located in mountain country. The sag and tension design data for this line are contained in data sheets 1 and 2 as shown in Figures 2 and 3, and it is suggested that these be studied to determine the solution procedure of this paper. These data sheets are coded to show the sequence of calculations. The left-hand number gives the calculation sequence, the numbers in parentheses the previous values used to derive the present value, and the right-hand key letter the formula used. Where no key letter is shown the value is obtained by using Table I. S values result from subtracting V from Y.

Data sheet number 1, shown in Figure 2, covers calculations for the basic (ruling) span where X is constant. Data sheet number 2, shown in Figure 3, covers calculations for other length spans related to the basic span where X varies with the span length, but the V value for each final or initial condition remains constant throughout varying span lengths.

While the data sheets are largely self-explanatory the steps in problem solution are further explained in the following paragraphs

1. Tabulate the cable characteristics, the per-foot cable loading values, the basic design span, and design final tension, item 1.

2. Calculate Y, item 2, for design load conditions using formula G. Use Table I to secure related values of V, item 3, and Z, item 4. Design sag item 5 is simply $Y-V$. Horizontal longitudinal component of tension F (item 1A) is secured by formula H. The calculating steps just outlined are based on the tension at support in the basic design span. If the design is to be based on a desired F value for the basic span first tabulate item 1A and calculate V, item 3, using formula H. Use Table I to secure related design values of V, item 2, and Z, item 4. Sag is $Y-V$, and total tension, item 1, is solved by using formula G.

3. Solve for unstressed Z, item 6, all loads removed, but with the cable still at design temperature, using formula I.

4. Solve for unstressed Z at other temperatures, items 7, 8, 9, and 10, using the item 6 value of Z and formula J.

5. Determine related V and Y values for each unstressed Z value from Table I.

6. Calculate Z (cable only) at various temperatures, items 21 to 25 inclusive, using formula I.

7. Determine related V and Y values for each cable only load condition from Table I. Sags for each condition are $Y-V$.

8. Solve for Z values (initial conditions, not prestretched) at various temperatures, items 46 to 50 inclusive by the use of for-

Table I. Unit Values of V, Y, Z, and S, Catenary Functions

Function Σ/V	Function V/Σ	Difference in Σ/V	Function Y/Σ	Difference in Y/Σ	Function S/Σ	Difference in S/Σ	Function Z/Σ	Difference in Z/Σ
0.00	Infinity	Infinity	Infinity	Infinity	Infinity	Infinity	0.0000000	1.0000167
0.01	100.00000	50.000000	100.00500	49.995000	.00500000	.00500000	1.0000167	.0000500
0.02	50.000000	16.666667	50.01000	16.661667	.01000000	.00500000	1.0000667	.0000833
0.03	33.333333	8.333333	33.34833	8.328330	.01500000	.00500300	1.0001500	.0001167
0.04	25.000000	5.000000	25.020003	4.994997	.02000300	.00500300	1.0002667	.0001500
0.05	20.000000	3.333333	20.025006	3.328331	.02500600	.00500200	1.0004167	.0001834
0.06	16.666667	2.380953	16.696675	2.379947	.03000800	.00500600	1.0006001	.0002168
0.07	14.285714	1.785714	14.320728	1.780707	.03501400	.00500700	1.0008169	.0002501
0.08	12.500000	1.388889	12.540021	1.383880	.04002100	.00500900	1.0010670	.0002835
0.09	11.111111	1.111111	11.156141	1.106099	.04503000	.00501200	1.0013505	.0003170
0.10	10.000000	.909091	10.050042	.904078	.05004200	.00501300	1.0016675	.0003504
0.11	9.090909	.757576	9.145964	.752559	.05505500	.00501700	1.0020179	.0003838
0.12	8.333333	.641025	8.303405	.636005	.06007200	.00502000	1.0024017	.0004174
0.13	7.692308	.549451	7.757400	.544429	.06509200	.00502200	1.0028191	.0004507
0.14	7.142857	.476190	7.212971	.471163	.07011400	.00502700	1.0032698	.0004845
0.15	6.666667	.416667	6.741808	.411637	.07514100	.00503000	1.0037543	.0005178
0.16	6.250000	.367647	6.330171	.362613	.08017100	.00503400	1.0042721	.0005516
0.17	5.882353	.326797	5.967558	.321759	.08520500	.00503800	1.0048237	.0005852
0.18	5.555556	.292398	5.645799	.287355	.09024300	.00504300	1.0054089	.0006186
0.19	5.263158	.263158	5.358444	.258110	.09528600	.00504800	1.0060275	.0006525
0.20	5.000000	.238095	5.100334	.233042	.10033400	.00505300	1.0066800	.0006863
0.21	4.761905	.216450	4.867292	.211392	.10538700	.00505800	1.0073663	.0007200
0.22	4.545455	.197629	4.655900	.192567	.11044500	.00506200	1.0080863	.0007537
0.23	4.347826	.181159	4.463333	.176080	.11550700	.00507000	1.0088400	.0007875
0.24	4.166667	.166667	4.287244	.161592	.12057700	.00507500	1.0096278	.0008215
0.25	4.000000	.153846	4.125652	.148764	.12565200	.00508200	1.0104493	.0008555
0.26	3.846154	.142450	3.976888	.137342	.13073400	.00508800	1.0113048	.0008897
0.27	3.703704	.132275	3.839526	.127180	.13582200	.00509500	1.0121945	.0009236
0.28	3.571429	.123153	3.712346	.118051	.14091700	.00510200	1.0131181	.0009577
0.29	3.448276	.114943	3.594295	.109834	.14601900	.00510900	1.0140758	.0009917
0.30	3.333333	.107527	3.484461	.102410	.15112800	.00511700	1.0150675	.0010262
0.31	3.225806	.100806	3.382051	.095681	.15624500	.00512500	1.0160937	.0010606
0.32	3.125000	.094697	3.286370	.089564	.16137000	.00513300	1.0171543	.0010948
0.33	3.030303	.089126	3.196806	.083985	.16650300	.00514100	1.0182491	.0011294
0.34	2.941177	.084034	3.112821	.078884	.17164400	.00515000	1.0193785	.0011636
0.35	2.857143	.079365	3.033937	.074206	.17679400	.00515900	1.0205421	.0011984
0.36	2.777778	.075075	2.959731	.069908	.18195300	.00516700	1.0217405	.0012330
0.37	2.702703	.071124	2.889823	.065947	.18712000	.00517700	1.0229735	.0012675
0.38	2.631579	.067476	2.823876	.062289	.19229700	.00518700	1.0242410	.0013027
0.39	2.564103	.064103	2.761587	.058906	.19748400	.00519700	1.0255437	.0013371
0.40	2.500000	.060976	2.702681	.055769	.20268100	.00520700	1.0268808	.0013722
0.41	2.439024	.058072	2.646912	.052855	.20788800	.00521700	1.0282530	.0014073
0.42	2.380952	.055371	2.594057	.050143	.21310500	.00522800	1.0296603	.0014423
0.43	2.325581	.052854	2.543914	.047615	.21833300	.00523900	1.0311026	.0014777
0.44	2.272727	.050505	2.496299	.045254	.22357200	.00525100	1.0325803	.0015130
0.45	2.222222	.048309	2.451045	.043048	.22882300	.00526100	1.0340933	.0015484
0.46	2.173913	.046253	2.407997	.040979	.23408400	.00527400	1.0356417	.0015840
0.47	2.127660	.044327	2.367018	.039041	.23935800	.00528600	1.0372257	.0016189
0.48	2.083333	.042517	2.327977	.037220	.24464400	.00529700	1.0388446	.0016550
0.49	2.040816	.040816	2.290757	.035505	.24994100	.00531100	1.0404996	.0016910
0.50	2.000000	.039216	2.255253	.033893	.25525200	.00532300	1.0421906	.0017265
0.51	1.960784	.037707	2.221359	.032370	.26057500	.00533700	1.0439171	.0017628
0.52	1.923077	.036285	2.188989	.030936	.26591200	.00534900	1.0456799	.0017985
0.53	1.886792	.034940	2.158053	.029576	.27126100	.00536400	1.0474784	.0018352
0.54	1.851852	.033671	2.128477	.028294	.27662500	.00537700	1.0493136	.0018707
0.55	1.818181	.032467	2.100183	.027075	.28200200	.00539200	1.0511843	.0019079
0.56	1.785714	.031328	2.073108	.025922	.28739400	.00540600	1.0530922	.0019443
0.57	1.754386	.030248	2.047186	.024827	.29280000	.00542100	1.0550365	.0019808
0.58	1.724138	.029223	2.022359	.023787	.29822100	.00543600	1.0570173	.0020174
0.59	1.694915	.028248	1.998572	.022796	.30365700	.00545200	1.0590347	.0020548
0.60	1.666667	.027323	1.975776	.021856	.30910900	.00546700	1.0610895	.0020911
0.61	1.639344	.026441	1.953920	.020959	.31457600	.00548200	1.0631806	.0021286
0.62	1.612903	.025601	1.932961	.020101	.32005800	.00550000	1.0653092	.0021663
0.63	1.587302	.024802	1.912860	.019287	.32555800	.00551500	1.0674755	.0022030
0.64	1.562500	.024038	1.893573	.018506	.33107300	.00553200	1.0696785	.0022411
0.65	1.538462	.023310	1.875067	.017761	.33660500	.00555000	1.0719196	.0022785
0.66	1.515152	.022615	1.857306	.017048	.34215500	.00556600	1.0741981	.0023157
0.67	1.492537	.021949	1.840258	.016365	.34772100	.00558400	1.0765138	.0023542
0.68	1.470588	.021313	1.823893	.015711	.35330500	.00560200	1.0788680	.0023929
0.69	1.449275	.020704	1.808182	.015084	.35890700	.00562000	1.0812602	.0024305
0.70	1.428571	.020120	1.793098	.014482	.36452700	.00563800	1.0836907	.0024694
0.71	1.408451	.019562	1.778616	.013904	.37016500	.0056 58	1.0861601	.0025073
0.72	1.388889	.019026	1.764712	.013349	.37582300	.00567700	1.0886674	.0025460
0.73	1.369863	.018512	1.751363	.012817	.38150000	.00569500	1.0912134	.0025847
0.74	1.351351	.018018	1.738546	.012302	.38719500	.00571600	1.0937981	.0026239
0.75	1.333333	.017543	1.726244	.011807	.39291100	.00573600	1.0964220	.0026638

Table I. Unit Values of V, Y, Z, and S Catenary Functions (continued)

Function X/V	Function V/X	Difference in V/X	Function Y/X	Difference in Y/X	Function S/X	Difference in S/X	Function Z/X	Difference in Z/X
0.76	1.315790		1.714437		.39864700		1.0990858	
		.017089		.011334		.00575500		.0027017
0.77	1.298701		1.703103		.40440200		1.1017875	
		.016650		.010874		.00577600		.0027419
0.78	1.282051		1.692229		.41017800		1.1045294	
		.016228		.010430		.00579800		.0027820
0.79	1.265823		1.681799		.41597600		1.1073114	
		.015823		.010005		.00581800		.0028211
0.80	1.250000		1.671794		.42179400		1.1101325	
		.015432		.009593		.00583900		.0028614
0.81	1.234568		1.662201		.42763300		1.1129939	
		.015056		.009194		.00586200		.0029012
0.82	1.219512		1.653007		.43349500		1.1158951	
		.014693		.008810		.00588300		.0029417
0.83	1.204819		1.644197		.43937800		1.1188368	
		.014343		.008437		.00590600		.0029823
0.84	1.190476		1.635760		.44528400		1.1218191	
		.014005		.008076		.00592900		.0030236
0.85	1.176471		1.627684		.45121300		1.1248427	
		.013680		.007728		.00595200		.0030638
0.86	1.162791		1.619956		.45716500		1.1279065	
		.013366		.007392		.00597400		.0031043
0.87	1.149425		1.612564		.46313900		1.1310108	
		.013061		.007062		.00599900		.0031468
0.88	1.136364		1.605502		.46913800		1.1341576	
		.012768		.006745		.00602300		.0031877
0.89	1.123596		1.598757		.47516100		1.1373453	
		.012485		.006439		.00604600		.0032287
0.90	1.111111		1.592318		.48120700		1.1405740	
		.012210		.006139		.00607100		.0032712
0.91	1.098901		1.586179		.48727800		1.1438452	
		.011944		.005847		.00609700		.0033137
0.92	1.086957		1.580332		.49337500		1.1471589	
		.011688		.005567		.00612100		.0033550
0.93	1.075269		1.574765		.49949600		1.1505139	
		.011439		.005292		.00614700		.0033978
0.94	1.063830		1.569473		.50564300		1.1539117	
		.011198		.005025		.00617300		.0034407
0.95	1.052632		1.564448		.51181600		1.1573524	
		.010965		.004766		.00619990		.0034832
0.96	1.041667		1.559682		.51801500		1.1608356	
		.010739		.004513		.00622600		.0035261
0.97	1.030928		1.555169		.52424100		1.1643617	
		.010520		.004268		.00625200		.0035693
0.98	1.020408		1.550901		.53049300		1.1679310	
		.010307		.004027		.00628000		.0036133
0.99	1.010101		1.546874		.53677300		1.1715443	
		.010101		.003793		.00630800		.0036569
1.00	1.00000		1.543081		.54308100		1.1752012	
		.009901		.003566		.00633500		.0037008
1.01	.990 .9		1.539515		.54941600		1.1789020	
		.009707		.003344		.00636300		.0037448
1.02	.9 0392		1.536171		.55577900		1.1826468	
		.009518		.003126		.00639200		.0037898
1.03	970874		1.533045		.56217100		1.1864366	
		.009336		.002915		.00642100		.0038332
1.04	.961538		1.530130		.56859200		1.1902698	
		.009157		.002707		.00645000		.0038795
1.05	.952381		1.527423		.57504200		1.1941493	
		.008984		.002505		.00648000		.0039236
1.06	.943396		1.524918		.58152200		1.1980729	
		.008817		.002308		.00650900		.0039691
1.07	.934579		1.522610		.58803100		1.2020420	
		.008653		.002112		.00654100		.0040155
1.08	.925926		1.520498		.59457200		1.2060575	
		.008495		.001925		.00657000		.0040604
1.09	.917431		1.518573		.60114200		1.2101179	
		.008341		.001738		.00660200		.0041072

Function X/V	Function V/X	Difference in V/X	Function Y/X	Difference in Y/X	Function S/X	Difference in S/X	Function Z/X	Difference in Z/X
1.10	.909091		1.516835		.60774400		1.2142251	
		.008190		.001557		.00663300		.0041531
1.11	.900901		1.515278		.61437700		1.2183782	
		.008044		.001379		.00666500		.0041995
1.12	.892857		1.513899		.62104200		1.2225777	
		.007901		.001204		.00669700		.0042471
1.13	.884956		1.512695		.62773900		1.2268248	
		.007763		.001034		.00672900		.0042934
1.14	.877193		1.511661		.63446800		1.2311182	
		.007628		.000866		.00676200		.0043407
1.15	.869565		1.510795		.64123000		1.2354589	
		.007496		.000700		.00679600		.0043890
1.16	.862069		1.510095		.64802600		1.2398479	
		.007368		.000539		.00682900		.0044368
1.17	.854701		1.509556		.65485500		1.2442847	
		.007243		.000380		.00686300		.0044852
1.18	.847458		1.509176		.66171800		1.2487699	
		.007122		.000226		.00689600		.0045324
1.19	.840336		1.508950		.66861400		1.2533023	
		.007003		.000071		.00693200		.0045817
1.20	.833333		1.508879		.67554600		1.2578840	
		.006887		.000080		.00696700		.0046310
1.21	.826446		1.508959		.68251300		1.2625150	
		.006774		.000228		.00700200		.0046805
1.22	.819672		1.509187		.68951500		1.2671955	
		.006664		.000375		.00703900		.0047299
1.23	.813008		1.509562		.69655400		1.2719254	
		.006556		.000518		.00707400		.0047805
1.24	.806452		1.510080		.70362800		1.2767059	
		.006452		.000659		.00711100		.0048294
1.25	.800000		1.510739		.71073900		1.2815353	
		.006349		.000799		.00714800		.0048807
1.26	.793651		1.511538		.71788700		1.2864160	
		.006249		.000937		.00718600		.0049315
1.27	.787402		1.512475		.72507300		1.2913475	
		.006152		.001071		.00722300		.0049816
1.28	.781250		1.513546		.73229600		1.2963291	
		.006056		.001205		.00726100		.0050340
1.29	.775194		1.514751		.73955700		1.3013631	
		.005963		.001337		.00730000		.0050853
1.30	.769231		1.516088		.74685700		1.3064484	
		.005872		.001467		.00733900		.0051373
1.31	.763359		1.517555		.75419600		1.3115857	
		.005783		.001596		.00737900		.0051897
1.32	.757576		1.519151		.76157500		1.3167754	
		.005696		.001722		.00741800		.0052425
1.33	.751880		1.520873		.76899300		1.3220179	
		.005611		.001848		.00745900		.0052953
1.34	.746269		1.522721		.77645200		1.3273132	
		.005528		.001971		.00749900		.0053485
1.35	.740741		1.524692		.78395100		1.3326617	
		.005447		.002092		.00753900		.0054015
1.36	.735294		1.526784		.79149000		1.3380632	
		.005367		.002215		.00758200		.0054564
1.37	.729927		1.528999		.79907200		1.3435196	
		.005289		.002335		.00762400		.0055111
1.38	.724638		1.531334		.80669600		1.3490307	
		.005214		.002451		.00766500		.0055637
1.39	.719424		1.533785		.81436100		1.3545944	
		.005138		.002572		.00771000		.0056215
1.40	.714286		1.536357		.82207100		1.3602159	
		.005066		.002685		.00775100		.0056759
1.41	.709220		1.539042		.82982200		1.3658918	
		.004995		.002800		.00779500		.0057295
1.42	.704225		1.541842		.83761700		1.3716213	
		.004924		.002924		.00784800		.0057887
1.43	.699301		1.544766		.84546500		1.3774100	
		.004857		.003019		.00787600		.0058419
1.44	.694444		1.547785		.85334100		1.3832519	

In a given span V, Y, S, and Z bear definite interrelationships expressed by the formulas, $Y = V \cosh (X/V)$, $Z = V \sinh (X/V)$, and $S = Y - V$. When these formulas are divided by X, unit values, $(Y/X) = (V/X) \cosh (X/V)$, $(Z/X) = (V/X) \sinh (X/V)$, and $(S/X) = (Y/X) - (V/X)$ result which apply to any length span.

Related unit values are tabulated in Table I. If V, Y, Z, or S is known for any span the other values can be quickly determined by the use of this table.

Differences for interpolations speed these calculations.

These tables also will supply cosh and sinh values for use in the formulas $Y = V \cosh (X/V)$ and $Z = V \sinh (X/V)$. The Y/X value of the table when multiplied by X/V becomes the cosh (X/V) of X/V, and Z/X value when multiplied by X/V becomes the sinh (X/V) of X/V.

CATENARY DATA SHEET

SPANS WITH SUPPORTS AT UNEQUAL ELEVATIONS

Conductor - ⅜ BHD Stranded Copper	Basic Span - 2000 ft.
Loading - 0° Fahr. - ½" Ice - 8 lb. Wind	V-Function - 24099899
Horizontal Span Length, l = 1440 ft.	Diff. in elev. D = 113 ft.
D/V = .004688817	(D/V)² = .000219850
l/V = 0.59751291	Cash(l/V) = 1.1838965
	Sinh(l/V) = .063371909
X_L (Form 5) = V log$_e$ [illegible]	= 5335.958 ft.
Xu (form 1) = (-5335.958) + 14400000	= 9064042 ft.
Yu (form 3) = 24099898 × 1.0246177	= 24691.182 ft.
Yu (form 2) = 2469.3182 + 113.00	= 2582.3182 ft.
X_S / (form 6) = (Func. with Sinh.) = .07848264	= .078401784
Xs (form 7) = V times 0.078401784	= 1889.475 ft.
Ys (form 8) = 24099898 × 1.0030817	= 24174.167 ft.
Yu (form 9) = 113.188.9475 - (5335.958) l/1440 = 2469.3182 - 2526.0178 ft.	
S_s (sag) (form 10) = 2526.0178 - 2417.4167	= 108.6011 ft.
Su (form 11) = 2582.3182 - 2409.9898	= 172.3284 ft.
S_L (form 12) = 2469.3182 - 2409.9898	= 59.3284 ft.
Zu (form 13) = 24099898 × .38503724	= 9279.358 ft.
ZL (form 14) = 24099898 × (-.02232481)	= -537.9695 ft.
L (form 15) = 9279.358 - (-537.9695)	= 14659.053 ft.

Sketch and Remarks

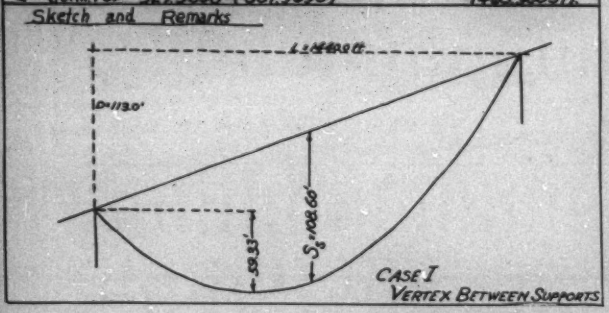


Figure 4

mula K. For this problem the following Ku values were used:

Ku—design loading = 0.00049
Ku—stringing = 0.00008
Ku (for formula K) = 0.00041

The stress-strain chart from which these values were secured is reproduced in Figure 4. It should be noted that the Ku values for stringing (initial) conditions varies very little over the range of stringing stresses encountered. This indicates that even with a variation between assumed stringing tensions used to secure Ku (stringing) and the final determined stringing tension, close stringing sag and tension values are secured. Stringing temperature variations have practically no effect on the Ku value taken from the stress-strain chart.

9. Determine related V and Y values (initial) from Table I. Solve for stringing sags, $Y - V$.

10. Solve for T and F (if desired) under various conditions. The cable loading per foot, and the Y and V values for each condition give the T and F values.

11. Solve for sags under various final and initial conditions for other span lengths. Remembering that the V value for a given final or initial condition is the same for all span lengths (related to the design span), use these V values and Table I to secure these sags. Tabulate these sags on data sheet number 2 (Figure 3). F values for the related spans are the same as the value for the design span under like final or initial conditions. If desired, the T value can be quickly determined for any related span by means of Table I and formula G.

The procedure outlined here gives full sag and tension data for final and initial conditions, not only for the design span, but also for similar conditions in other related span lengths.

The calculation procedure can be reversed, if it is desired to base the calculations on other conditions such as final, cable only at 60 degrees Fahrenheit.

Hillside Span Calculations

Several approximate methods of determining sags in hillside spans are in use. One of the best of these methods is published in Martin's tables. Martin has also developed another method of calculating hillside spans which has an extremely high degree of mathematical accuracy.

The appendix outlines a mathematically exact method, developed by the writers and their associates, for determining sag, deflection of vertex below supports, and horizontal distances from the vertex to supports in hillside spans This method is recommended where precision results are desired.

Appendix. Hillside Span Calculations

This paper outlines a mathematically accurate method, developed by the authors, of determining sag, deflection of vertex below supports, and distance (horizontally) from the vertex to supports in spans with supports at unequal elevations. Its use is recommended whenever precision results are necessary, such as with certain span designs crossing railroads, highways, or other lines.

The method is based on maintaining the same horizontal longitudinal component of tension, and therefore the same V value, as in the ruling span to which the hillside span is related.

The procedure outlined is applicable to any type cable such as copper, copper-coated steel, steel, or aluminium cable steel reinforced, where the ruling span sag (for a level span) is known.

There are two general types of spans with supports at unequal elevations:

Case I. Catenary vertex located between supports.

Case II. Catenary vertex located below the lower support.

Figure 5 illustrates these two conditions.

Nomenclature (Refer to Figure 5)

D = difference in elevation of cable supports
l = span length (horizontally)
X_u, Y_u = co-ordinates of upper support
X_L, Y_L = co-ordinates of lower support
S_s = sag of cable, which is the maximum deflection of the cable from the straight (slope) line between supports
X_s, Y_s = co-ordinates of catenary curve at the point of maximum deflection, S_s
Y_J = Y co-ordinate of a point on the slope line (between supports) directly above Y_s
S_u = deflection of vertex below upper support
S_L = deflection of vertex below lower support
Z_u = catenary length from vertex to upper support
Z_L = catenary length from vertex to lower support
L = catenary length of span (hillside span)

V = the ruling (basic) span V value for the cable under the assumed loading conditions

If this V value is not known, it may be quickly determined as follows:

Divide ruling span sag (level span) by X (1/2 span), to secure S/X. From Table I determine by interpolation the corresponding V/X value. This multiplied by X (1/2 span), gives the required V value.

This procedure may be used with any type cable.

The various formulas and their derivation are given in the following. In developing these formulas the writers have assumed that the upper support is to the right of the lower support. Under case I conditions the lower-support X and Z values should be set in the formulas as minus quantities since they are to the left-hand (minus) side of the vertex.

$$l = X_u - X_L \tag{1}$$

or

$$X_u = X_L + l$$

Case II—As X_u and X_L are on the same side of the vertex, both represent positive values.

Case I—As X_u and X_L are on opposite sides of the vertex, X_L is taken as a negative value.

$$Y_u = Y_L + D \tag{2}$$

$$Y_u = V \cosh\,(X_u/V)$$

$$Y_u = V \cosh\left(\frac{X_L + l}{V}\right)$$

$$Y_L = V \cosh\,(X_L/V) \tag{3}$$

$$D = Y_u - Y_L$$

Therefore:

$$D/V = \cosh\left(\frac{X_L+l}{V}\right) - \cosh\left(\frac{X_L}{V}\right)$$

$$\frac{D}{V} = \frac{\epsilon^{\left(\frac{X_L+l}{V}\right)} + \epsilon^{-\left(\frac{X_L+l}{V}\right)}}{2} - \frac{\epsilon^{(X_L/V)} + \epsilon^{-(X_L/V)}}{2}$$

Transpose and rearrange:

$$\frac{2D}{V} = \epsilon^{(X_L/V)}[\epsilon^{(l/V)} - 1] + \epsilon^{-(X_L/V)}[\epsilon^{-(l/V)} - 1]$$

Multiply by $\epsilon^{(X_L/V)}$:

$$\frac{2D\epsilon^{(X_L/V)}}{V} = [\epsilon^{(X_L/V)}]^2[\epsilon^{(l/V)} - 1] + [\epsilon^{-(l/V)} - 1]$$

Transpose:

$$[\epsilon^{(X_L/V)}]^2[\epsilon^{(l/V)} - 1] - \frac{2D}{V}\epsilon^{(X_L/V)} = -\epsilon^{-(l/V)} - 1]$$

Multiply by $[\epsilon^{(l/V)} - 1]$ and add $(D/V)^2$:

$$[\epsilon^{(X_L/V)}]^2[\epsilon^{(l/V)} - 1]^2 - \frac{2D}{V}\epsilon^{(X_L/V)}[\epsilon^{(l/V)} - 1] + \left(\frac{D}{V}\right)^2 = \epsilon^{(l/V)} + \epsilon^{-(l/V)} - 2 + \left(\frac{D}{V}\right)^2$$

Extract square root:

$$[\epsilon^{(X_L/V)}][\epsilon^{(l/V)} - 1] - \frac{D}{V} = \sqrt{\epsilon^{(l/V)} + \epsilon^{-(l/V)} - 2 + \left(\frac{D}{V}\right)^2}$$

$$\epsilon^{(X_L/V)} = \frac{\frac{D}{V} + \sqrt{2\cosh\,(l/V) - 2 + \left(\frac{D}{V}\right)^2}}{[\epsilon^{(l/V)} - 1]}$$

$$\epsilon^{(X_L/V)} = \frac{\frac{D}{V} + \sqrt{\left(\frac{D}{V}\right)^2 + 2\,[\cosh\,(l/)V - 1]}}{[\cosh\,(l/V) + \sinh\,(l/V) - 1]} \tag{4}$$

$$X_L = V \times \log_e \left[\frac{\frac{D}{V} + \sqrt{\left(\frac{D}{V}\right)^2 + 2[\cosh\,(l/V) - 1]}}{\cosh\,(l/V) + \sinh\,(l/V) - 1}\right] \tag{5}$$

After X_L is determined, Y_L is found by equation 3.

$$\frac{D}{l} = \sinh\left(\frac{X_s}{V}\right)$$

The slope of the catenary curve at point X_s is the sinh at that point, since the sinh is the derivative of cosh (X_s/V)

$$\frac{X_s}{V} = \sinh^{-1}\left(\frac{D}{l}\right) \tag{6}$$

X_s/V = function which has its sinh = D/l

X_s = formula 6 value multiplied by V (7)

$$Y_s = V \cosh\,(X_s/V) \tag{8}$$

CATENARY DATA SHEET

SPANS WITH SUPPORTS AT UNEQUAL ELEVATIONS

Conductor - ⅜ B.H.D. Stranded Copper	Basic Span - 2000 ft
Loading - 0° Fahr. - ½" Ice - 8 lb Wind	V - Function - 2409.9898
Horizontal Span Length l = 1225 ft	Diff. in elev. D = 355 ft
D/V = 0.14730353	$(D/V)^2$ = 0.02169833
l/V = 0.50830091	D/l = 0.28979592
Cosh (l/V) = 1.1319984	Sinh (l/V) = 0.53047741
X_L (Form 5) = $V \log_e$ [0.14730353 + √(0.02169833 + 0.53047741 − 1)]	= 69.3595 ft
X_u (form 1) = 69.3595 + 1225.0000	= 1294.3595 ft.
Y_L (form 3) = 2409.9898 × 1.0041195	= 2411.0008 ft.
Y_u (form 2) = 2411.0008 + 355.0000	= 2766.0008 ft.
X_s / (form 6) = (Func with Sinh = 0.28979592	= 28.588234
X_s (form 7) = V times 2.859	= 68.90161 ft.
Y_s (form 8) = 2409.9898 × 1.0411560	= 2509.1753 ft.
Y_u (form 9) = 355 + 689.0161 − 69.3595) / 1225 × 2411.0008 =	2590.5748 ft.
S (sag) (form 10) = 2590.5748 − 2509.1753	= 81.3995 ft.
S_u (form 11) = Not Required	=
S_L (form 12) = Not Required	=
Z_u (form 13) = 2409.9898 × 0.56328237	= 1357.5048 ft.
Z_L (form 14) = 2409.9898 × 0.28284112	= 69.3694 ft.
L (form 15) = 1357.5048 − 69.3694	= 1288.1354 ft.

Sketch and Remarks

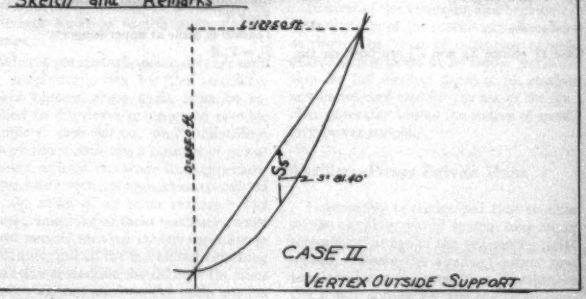


Figure 5

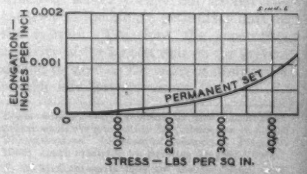
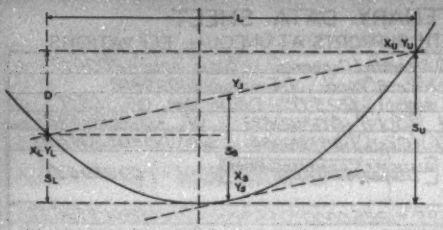


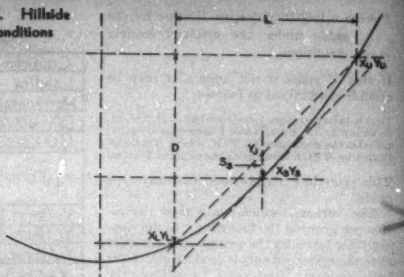
Figure 6. Stress-strain chart

Seven-strand hard-drawn copper cable



CASE I

Figure 7. Hillside sag conditions



CASE II

By proportion:

$$(Y_J - Y_L)/(X_S - X_L) = D/l$$

$$Y_J = D(X_S - X_L)/l + Y_L \quad (9)$$

$$S_S = Y_J - Y_S \quad (10)$$

$$S_U = Y_U - V \quad (11)$$

$$S_L = Y_L - V \quad (12)$$

$$Z_U = V \sinh (X_U/V) \quad (13)$$

$$Z_L = V \sinh (X_L/V) \quad (14)$$

$$L = Z_U - Z_L \quad (15)$$

Case II—Since Z_U and Z_L are both on the same side of the vertex, and originate at the vertex, both represent positive values.

Case I—Since Z_U and Z_L are on opposite sides of the vertex, and L is equal arithmetically to $Z_U + Z_L$, Z_L represents a negative value (algebraic).

Sample problems, case I and case II, are shown in Figures 6 and 7 which explain the procedure used in solving hillside problems. Tension values at supports in case-I problems are found as follows:

Horizontal longitudinal component:
$F = VR$
Tension in cable at upper support:
$T_U = Y_U R$

Tension in cable at lower support:
$T_L = Y_L R$

References

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Auxiliary-Power Supply for Generating Stations

V. E. McCALLUM
MEMBER AIEE

Synopsis: Industry, in general, has been adopting the electric motor drive and its control to all types of machines. In the central station, where sequential and correlated operation is a necessity, the use of electric-motor-driven auxiliaries also has shown a marked increase. All recent stations have been built with a major portion of their auxiliaries driven by electric motors. The author suggests the use of the station generator bus as the most reliable source of auxiliary-power supply in electric stations of a closely interconnected system similar to that in the Chicago area. Separate auxiliary service units, not exceeding in size the requirements of the largest turbogenerator unit, also are recommended.

THE PRESENT ELECTRIC generating station is dependent at all times on the integrity of the auxiliary-power system. Therefore, this system must be designed for maximum reliability. Other desirable characteristics of the auxiliary-power system are: safety of personnel, flexibility, simplicity of operation, ease of maintenance, and reasonable cost.

The auxiliaries of the modern electric station consume approximately five per cent to seven per cent of the gross output. Therefore, when designing an auxiliary-power system, the engineer should bear in mind that he is designing the equivalent of approximately 1/20th of the entire conversion and distribution system fed from the station. He also should bear in mind that on the integrity of this 1/20th rests to a large degree the usefulness of the remaining 19/20ths.

An ideal auxiliary-power-supply system, regardless of its size, always should remain a simple system. The tendency to cross-connect and interconnect should be strongly curbed. Dependency should be placed on sturdy, rugged, and well-insulated equipment rather than on complicated switching and relay arrangements designed to remedy faulted conditions.

Trend to Electric Drive

In electric stations on a closely interconnected system similar to that in the Chicago area there has been a steady trend from individual steam drive to electric drive for all station auxiliaries.

The modern induction motor has become the simplest and most reliable of rotating machines, and it is being adopted by the industry as a universal drive. New insulations have been developed to withstand boiler-room temperature with continuous operation. In those applications where variable speed is a necessity, the wound-rotor induction motor is available, but with some sacrifice of reliability and simplicity and somewhat higher first cost.

Early Sources of Auxiliary-Power Supply

Several sources of electric power have been used to provide service for the auxiliary motors. The most common was the turbine connected to an auxiliary generator. Other sources were the shaft alternator on the main turbine and the transformer directly connected to either the generator leads or to the main station busses.

When separate turbogenerators are used for supplying power for the auxiliary-power centers, these units must be installed in duplicate in order to provide complete segregation and reliability. Where the station has a number of power centers, at least one spare turbogenerator is necessary with the connections provided for the relief of all other centers. The cross-connecting of these auxiliary-power units necessitates an excess capacity in each unit, and all the associated switching and relay protection should be of the same quality as that used on the main station busses.

The installation of the auxiliary-power generator on the shaft on the main unit has been supplanted in some cases with a transformer connected to the generator leads. There are some disadvantages of the shaft alternator or transformer on the generator leads, as these units are potential sources of outage of the main unit and they introduce the problem of changing the power source for the auxiliaries in the starting and stopping periods. If the auxiliary-power transformer is disconnected from the generator leads and reconnected to the main bus to which the unit itself is connected, the principle has not been changed, but there is greater flexibility, and there is no need for switching operations during the starting and stopping periods.

Station Bus as the Source of Auxiliary-Power Supply

The main bus of a station to which the generators are connected is the simplest type of electrical equipment, and it lends itself readily to a high order of mechanical and electrical protection. When the busses are divided into sections with each section in a separate bus chamber and equipped with either balanced relays or fault bus protection, it is difficult to conceive any major fault which would shut down more than one or two adjacent sections of a station bus. As each section of the bus is supported by the adjoining sections and as the entire station bus is supported by all generators in the station and also by transmission lines from other stations, during disturbances, these transmission lines become, in effect, auxiliary-power-supply lines for the station in distress.

This supporting function of the transmission lines makes it unnecessary to provide self-starting auxiliary-power generation equipment in more than one or two stations on the entire system.

Where the power system is so constructed that it will sectionalize automatically during trouble, a complete shutdown of any section will not prove disastrous to the system as a whole.

In view of the foregoing and because of the reliability of the station generator bus as proved by years of operating experience, there appears to be ample justification for full electric drive of all station auxiliaries and also for the use of the station generator bus as the source of auxiliary-power supply.

Auxiliary-Power Service Units

It generally is recognized that trouble on the auxiliary-power system may cause temporary outage of the generating units served. Where the auxiliary-power system is so interconnected that it embraces the power supply for the entire station, any trouble on this system also may affect the entire station. It follows, therefore, that by designing the auxiliary-power system in noninterconnected units, it is possible to confine the effects of failure of any power unit to the generating capacity which it serves.

Because on any interconnected system there is a possibility of the loss of any of the larger generating units and the system is so set up as to sustain such loss without undue disturbance, it follows that the size of the auxiliary-power service unit should be such that the generating capacity which it serves should not exceed the capacity of the largest generating unit on the system. Therefore, the generating capacity of the largest unit on the system should be used as the basis of design of a reliable auxiliary-power supply.

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In spite of the inherently high reliability of power lines and transformers, two supply lines are still considered necessary for each auxiliary-power unit. These auxiliary-power supply lines should be equal in reliability and capacity so that either can be considered as a reserve for the other, and each should be capable of carrying the entire auxiliary service unit.

This principle is illustrated in Figure 1. Here the station busses are shown in their simplest form consisting of two bus sections connected by a tie circuit breaker. One of the auxiliary-power supply lines is connected to the bus supported by the generating capacity served by the auxiliary-power unit, and the other supply line is connected to a bus supported by a transmission line. It will be noted that each auxiliary-power center bus is fed from two transformers, one on each of the auxiliary-power supply lines. Section circuit breakers in these busses can be used for automatic power restoration in case of loss of either of the supply lines or to divide the busses for maintenance purposes.

To secure the maximum utilization of the equipment employed and to take advantage of its short-time overload capacity, the transformers supplying each bus could be selected to have a definite overload during the outage of the opposite transformer or of the power line which feeds it. When both transformers are in service, the total load of each bus will be divided between the two transformers, allowing a safe loading margin for this type of equipment.

Auxiliary-Power Centers

In designing the auxiliary-power center primary consideration must be given to features having a direct bearing on the reliability, ease of maintenance, and equipment life. Auxiliary-power centers should be located as near the load center as possible, and particular attention should be paid to the protection from external hazards such as water, smoke, and so forth. The room should be ventilated with filtered air and all auxiliary power switching equipment, relays, and associated control apparatus should be treated as any other vital station equipment. The switchgear should be of the draw-out type and easily interchangeable. The manufacturers are ready to furnish such equipment completely assembled which can be compactly and easily installed.

Separate auxiliary-power centers serving auxiliaries common to the entire station such as crib house and coal-handling equipment may be connected to the first pair of auxiliary-power lines to be installed to the station. These centers should be housed in the individual rooms with the same precautions taken as with the larger centers.

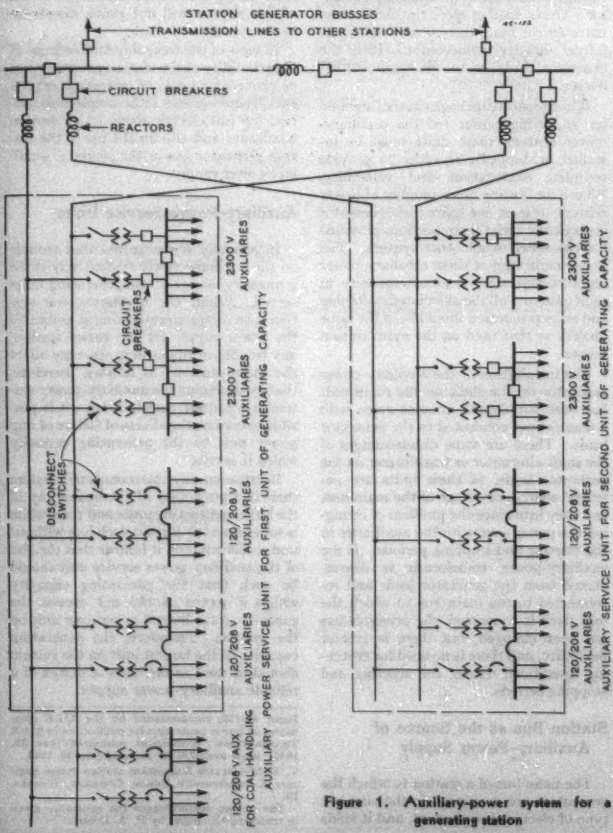

Figure 1. Auxiliary-power system for a generating station

Auxiliary-Power Voltages

In the interest of simplification and the reduction of kinds of equipment and voltages, it appears desirable to limit the number of voltages on two For large motors, that is, above 100 horsepower, the voltage of 2,300 is universally used, and, as the manufacturers are now ready to supply motors at this voltage in sizes as low as 60 horsepower, it would be difficult to justify the change of this voltage to a higher or lower value. Therefore, it is recommended as a standard voltage.

On the other hand, for the smaller motors and lighting requirements the 120–208-volt system has many advantages. Unless there are some other special reasons, this voltage should be used as the second standard voltage.

Conclusions

The essential characteristics of the power supply to the auxiliary motors of a generating station may be summarized as follows:

1. In an electric power station on an interconnected system the station generator busses should be used as the source of auxiliary-power supply.

2. A separate and independent auxiliary-power service unit should be provided to serve the maximum amount of generating capacity, the loss of which could be sustained by the system without undue disturbance.

3. Each auxiliary-power center should be supplied by two lines operated in parallel, one line connected to the bus supported by the generator and one line to the bus supported by a transmission line.

4. There can be as many auxiliary-power center busses connected to the supply lines through transformers as are required by the design of the station and by the limitations of the switching equipment involved.

5. All contactors, circuit breakers, relays, and control apparatus should be installed in separate well-ventilated rooms.

Industrial Control: Heating of Shunt-Motor Starting Resistors

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THE USUAL METHOD of starting a shunt motor from a constant-potential source is to insert one or more steps of armature resistance which are short-circuited by contactors operated after a definite time. The required capacity of a resistor for this type of duty is directly related to load conditions and time setting of relays as well as duty-cycle requirements. If time settings are made arbitrarily without some co-ordination with the kind of load, the energy dissipated in the resistor may be unduly high, because the load may be up to speed in a time much less than the setting. On the other hand if the load has a high inertia, the definite time may be too short, causing excessively high peaks on switching points after the first one. Although d-c motors have been used extensively in this way, equations governing such operation do not appear to have been published.

In many industrial applications load data have not been well known to the electric-system designer. He has had to depend upon a systematic grouping into a single classification of various loads, based only on initial inrush current and duty cycle. Such a classification in one case includes conveyors, line shafting, boring mills, punch presses, ball mills, and coal crushers. A better approach to starting-resistor design requires more information on load characteristics as well as the effect of these characteristics on starting-resistor capacity.

Scope of Paper

This paper presents an analysis of conditions which exist when a d-c shunt motor with constant applied field is started by inserting one step of armature resistance. Two cases are treated:

(*a*). Constant-load torque.

(*b*). Load torque varying directly as the speed.

It is the purpose of this work to obtain theoretical expressions for the total energy dissipated in a resistor as a function of load inertia, torque, final speed, initial inrush current, and accelerating time. Relations existing between speed, current, and second current peak as a function of time and circuit parameters are examined.

Assumptions

1. The starting resistor is assumed to hold constant resistance independent of temperature.
2. Armature reaction is neglected. This is a fairly good assumption for currents of 200 per cent or less.
3. In this paper all curves are plotted for a motor internal resistance of ten per cent. In practice this internal resistance may vary from 12 per cent at five horsepower to 4.5 per cent at 150 horsepower.

Results

The co-ordinates of all curves shown are in dimensionless form, so that the data are applicable to any size motor or load.

Time Constant. The developed equation of speed for both torque cases is similar to the equation for current build-up in a *RL* circuit, which allows the concept of time constant to be used. For the constant-torque case the term $\Omega J/T_o$ is the time constant of the system, and for the variable-torque case the equivalent term is $\Omega J/(T_o + \Omega k)$. At one time constant the speed is 63.2 per cent of its ultimate speed, and after two-time constants the speed is 86.5 per cent of the final. All results obtained in this paper are presented as a function of the number of time constants rather than time in seconds. In general two time constants has been selected as a good switching time, and most curves are presented for this value.

Speed and Current Curves. The curves in Figures 4a, 4b, 5a, and 5b show the current and angular velocity during the accelerating time for various ratios of load torque to full-load torque. The parameter, *a*, in Figures 4a and 4b is the ratio of load torque to full-load torque and, *g*, in Figures 5a and 5b is the ratio of the load torque at the no-load angular velocity Ω, to the full-load torque.

Resistor Watt-Seconds. The curves in Figure 6 show the factor by which the $J\Omega^2$ of the system can be multiplied to give the watt-seconds generated per start in the starting resistor. They are plotted for the case where the resistor is short-circuited after two time constants. These curves show clearly that the energy dissipated in the resistor is decreased as the initial inrush is increased. For example for a fully loaded motor the watt-seconds decrease in the ratio 1.37 to 0.83 as the initial current is raised from 125 per cent to 200 per cent.

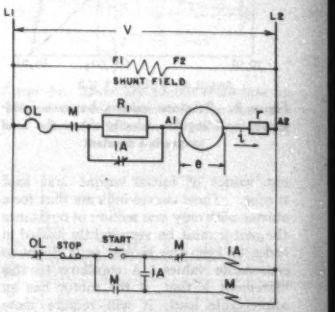

Figure 1. Elementary wiring diagram showing typical definite-time starting circuit

M = line contactor
IA = time accelerating contactor
OL = overload relay
R = total circuit resistance = $R_1 + r$
V = line voltage
e = counterelectromotive force
i = armature current
R_1 = external resistance
r = internal resistance

Figure 7 represents the same data as Figure 6 for the case where the load torque varies directly as the speed.

Although the curves in Figure 7 show that the watt-seconds in the resistor decrease as the load is increased, it should be noted that the switching speed also has decreased because of a decrease in $d = T_o/(T_o + \Omega k)$, and $t_1 = 2\Omega J/(T_o + \Omega k)$ as Ωk is increased.

Second Current Peak. Figure 8 shows how the second current peak varies in terms of the first current peak for differ-

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6. For simplicity it is recommended that only two voltages be employed for the auxiliaries and that the service to all motors be uniform and have the same method of operation.

7. The entire auxiliary-power system for any unit should be so protected by relays that in case of a fault on any part of the auxiliary service unit the faulted equipment would be automatically disconnected.

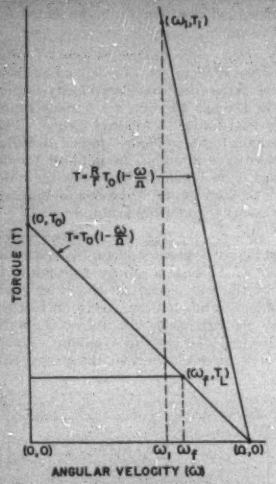

Figure 2. Relations existing between motor torque and angular velocity when the load torque is a constant

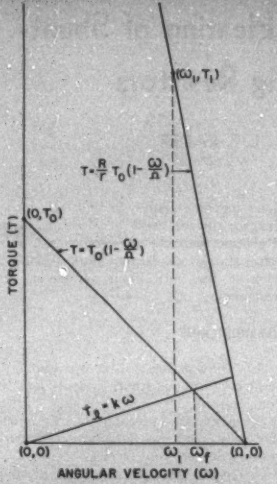

Figure 3. Relations existing between motor torque and angular velocity when the load torque varies directly as the speed

ent values of initial torque and load torque. These curves indicate that for a starter with only one section of resistance the motor must be very lightly loaded in order to keep the second peak down to reasonable values. A corollary to this statement is that, if the motor has an appreciable load, it will require more than one resistance step for good commutation.

Switching Time. Figure 9 shows how the watt-seconds generated in the resistor vary with the time allowed for acceleration. These curves indicate that, if a motor has an appreciable load (over 25-per-cent full load), it is important to short-circuit out the resistor as soon as possible consistent with a safe second current peak. For a switching time longer than two time constants Figure 9 shows how the heating severity on the resistor increases with only a slight gain in angular velocity. For example, if $a = T_L/T_{FL} = 0.75$ and $T_s = 2.0\ T_{FL}$ and switching occurs at two time constants, the speed is 86.5 per cent, $\omega_f = 62.5$ per cent Ω, and M is equal to 0.7. If switching occurs at three time constants, the speed is 95 per cent ω_f, and $M = 0.87$. This shows an increase of 24.3 per cent in watt-seconds in the resistor for a gain of only 9.8 per cent in speed. If the load is full load, then $a = 1.0$, and there is an increase of 31 per cent in watt-seconds for the same 9.8 per cent gain in speed.

Circuit Diagram

Figure 1 shows a typical definite time-starter connection diagram. When the start button is pressed the coil of the accelerating contactor $1A$ is energized, thus opening its normally closed power contact and closing its normally open control contact. When the control contact on $1A$ closes, it energizes the line contactor coil M which seals itself in through its own interlock. The closing of contactor M connects the motor armature to the line through the resistor R_1 and allows the initial current I_s to flow. Simultaneously, the coil of $1A$ is de-energized, so that after a definite time $1A$ drops out short-circuiting the resistor R_1 and allowing the second current peak I_1 to flow.

Speed–Torque Diagram

Figures 2 and 3 show relations between torque and angular velocity for the constant- and variable-torque case respectively. The developed motor torque is given by equation 8 and is shown as a straight line going through the points (O, T_s) and (Ω, O). The point of intersection of this line, with the load torque line determines the steady-state operating speed (ω_f) when resistance is in the armature circuit. The point ω_1 represents the speed at switching. The torque after switching rises to T_1 which is on the line given by equation 8a for a motor with internal resistance of r.

Analysis

For nomenclature used in this analysis see the appendix.

In a d-c motor the well-known equations for torque and back electromotive force are

$$T=\frac{c\phi i}{2\pi 10^8} \tag{1}$$

and

$$e=\frac{c\phi\omega}{2\pi 10^8} \tag{2}$$

Since $V = e + iR$, then

$$i=\frac{V-e}{R}=\frac{V}{R}-\frac{c\phi\omega}{R2\pi 10^8} \tag{3}$$

Putting equation 3 into equation 1 gives

$$T=\frac{c\phi V}{2\pi 10^8 R}-\left[\frac{c\phi}{2\pi 10^8}\right]^2\frac{\omega}{R}$$
$$=\frac{c\phi}{2\pi 10^8}\frac{V}{R}\left[1-\frac{c\phi\omega}{2\pi 10^8 V}\right] \tag{4}$$

With no load on the machine e becomes V, and $\omega = \Omega$, so that equation 2 resolves to

$$V=\frac{c\phi\Omega}{2\pi 10^8} \text{ and}$$

$$\Omega=\frac{2\pi 10^8 V}{c\phi} \tag{5}$$

Substituting equation 5 into equation 4 gives

$$T=\frac{c\phi}{2\pi 10^8}\frac{V}{R}\left[1-\frac{\omega}{\Omega}\right] \tag{6}$$

At $t = o$, $\omega = o$, and

$$T=T_s=\frac{c\phi}{2\pi 10^8}\frac{V}{R}=\frac{c\phi}{2\pi 10^8}I_s \tag{7}$$

Then equation 6 may be written

$$T=T_s\left(1-\frac{\omega}{\Omega}\right) \tag{8}$$

The torque equation for internal resistance r is

$$T=T_s\frac{R}{r}\left(1-\frac{\omega}{\Omega}\right) \tag{8a}$$

as initial torque is inversely proportional to circuit resistance. Dividing equation 7 by equation 5 gives the useful relationship,

$$\frac{T_s}{V}=\frac{V}{R\Omega}=\frac{I_s}{\Omega} \tag{9}$$

so that equating 6 and equation 1 gives the following equation for current

$$i=\frac{V}{R\Omega}(\Omega-\omega)=\frac{T_s}{V}(\Omega-\omega)=I_s\left(1-\frac{\omega}{\Omega}\right) \tag{10}$$

Case 1: Constant-Torque Load

The graphical representation for this case is shown in Figure 2.

The difference between generated motor torque, T, and load torque, T_L, causes acceleration, so that

$$T-T_L=\frac{Jd\omega}{dt} \tag{11}$$

Substituting for T from equation 8 gives

$$\frac{J\,d\omega}{dt}+T_s\frac{\omega}{\Omega}=T_s-T_L \tag{12}$$

whose solution is

$$\omega=\left(\frac{T_s-T_L}{T_s}\right)\Omega+A\,e^{-\frac{T_s t}{\Omega J}} \tag{13}$$

At $t=0, \omega=0$, so that

$$A=-\frac{(T_s-T_L)}{T_s}\Omega$$

and equation 13 becomes

$$\omega=\left(\frac{T_s-T_L}{T_s}\right)\Omega\left[1-e^{-\frac{T_s t}{\Omega J}}\right] \tag{14}$$

At $t=\infty$,

$$\omega=\omega_f=\left(\frac{T_s-T_L}{T_s}\right)\Omega \tag{15}$$

so that

$$\omega=\omega_f\left[1-e^{-\frac{T_s t}{\Omega J}}\right] \tag{16}$$

Putting the expression for ω from equation 14 into equation 10 yields

$$i=I_s\left[\frac{T_L}{T_s}+\left(\frac{T_s-T_L}{T_s}\right)e^{-\frac{T_s t}{\Omega J}}\right] \tag{17}$$

Let

$$\left(\frac{T_s-T_L}{T_s}\right)=b, \text{ so that } \frac{T_L}{T_s}=1-b$$

and the equation for current becomes

$$i=I_s\left[(1-b)+be^{-\frac{T_s t}{\Omega J}}\right] \tag{18}$$

The energy dissipated in the resistor in time t_1 is

$$E=\int_0^{t_1} i^2R_1dt=I_s^2R_1\times \int_0^{t_1}\left(1-b+be^{-\frac{T_s t}{\Omega J}}\right)^2dt \tag{19}$$

$$=I_s^2R_1\left[(1-b)^2t_1+2b(1-b)\frac{\Omega J}{T_s}\times\left(1-e^{-\frac{T_s t_1}{\Omega J}}\right)+\frac{b^2\Omega J}{2T_s}\times\left(1-e^{-\frac{2T_s t_1}{\Omega J}}\right)\right] \tag{20}$$

Let $t_1=\dfrac{2\Omega J}{T_s}$ so that equation 20 reduces to

$$E=\frac{I_s^2R_1\Omega J}{T_s}\,[2-2.27b+0.761b^2] \tag{21}$$

When the value for I_s from equation 9 is put in, equation 21 reduces to

$$E=J\Omega^2\left[\frac{R_1}{R}\right][2-2.27b+0.761b^2] \tag{22a}$$

or

$$E=J\Omega^2\left[\frac{R_1}{R}\right]\left[0.491+0.748\frac{T_L}{T_s}+0.761\left(\frac{T_L}{T_s}\right)^2\right] \tag{22b}$$

At $t_1=\dfrac{2\Omega J}{T_s}$ equation 14 becomes

$$\omega_1=\omega_f(1-e^{-2})=0.865\omega_f \tag{23}$$

Second Current Peak, I_1

At $t=t_1$ the timing relay 1A (Figure 1) drops out short-circuiting out the external resistance R_1, so that the resistance of the circuit changes from R to r.

Just before switching

$$i=I_s\left(1-\frac{\omega_1}{\Omega}\right) \text{ and } e_1=\frac{c\phi\omega_1}{2\pi 10^8}$$

Now

$$\frac{e_1}{V}=\frac{\omega_1}{\Omega}=\frac{0.865\omega_f}{\Omega} \tag{24}$$

The new current peak is given by

$$I_1=\frac{V-e_1}{r}=\frac{V}{r}\left[1-\frac{0.865\omega_f}{\Omega}\right] \tag{25}$$

The same relationship can be obtained by considering similar triangles in Figure 2. Equation 25 also can be written using the relationship of equation 15.

$$I_1=\frac{V}{r}\left[1-0.865\,\frac{T_s-T_L}{T_s}\right] \tag{26a}$$

$$=\frac{V}{r}\left[0.135+0.865\,\frac{T_L}{T_s}\right] \tag{26b}$$

$$=\frac{V}{r}\left[0.135+0.865\,\frac{I_L}{I_s}\right] \tag{26c}$$

since $\dfrac{T_L}{T_s}=\dfrac{I_L}{I_s}$ from equation 1.

If switching takes place at $t=\infty$ so that

$$i=I_s\left(1-\frac{\omega_f}{\Omega}\right)$$

then from equation 15 and equation 1

$$I_1=\frac{V}{r}\left[1-\left(1-\frac{I_L}{I_s}\right)\right]=\frac{V}{r}\,\frac{I_L}{I_s} \tag{27}$$

Case 2: Load Torque Directly Proportional to Speed

Let

$$T_L=k\omega \tag{28}$$

and

$$T_0=k\Omega$$

As before

$$T=T_s\left(1-\frac{\omega}{\Omega}\right)$$

These relationships are shown in Figure 3. Then

$$T-T_L=J\frac{d\omega}{dt}$$

so that

$$J\frac{d\omega}{dt}+\omega\left(\frac{T_s+k\Omega}{\Omega}\right)=T_s \tag{29}$$

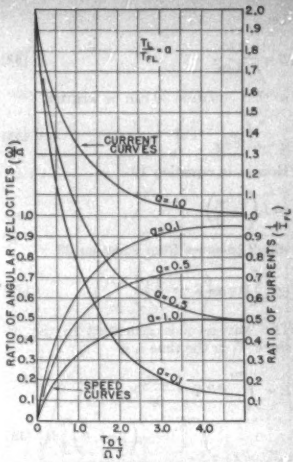

Figure 4a. Speed and current versus time for 200-per-cent initial torque and various ratios of a constant-load torque to full-load torque

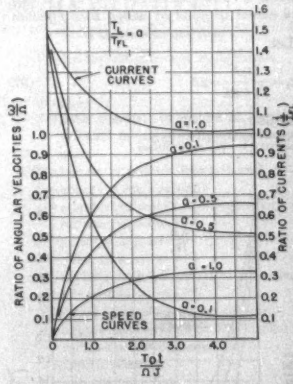

Figure 4b. Speed and current versus time for 150-per-cent initial torque and various ratios of a constant-load torque to full-load torque

and

$$\omega=\frac{T_s\Omega}{T_s+\Omega k}+Ce^{-\left(\frac{T_0+\Omega k}{\Omega J}\right)t}$$

At $t=0$, $\omega=0$, so that C is determined and

$$\omega=\frac{T_s\Omega}{T_s+\Omega k}\left[1-e^{-\left(\frac{T_0+\Omega k}{\Omega J}\right)t}\right] \tag{30}$$

At

$$T=\infty,\ \omega=\omega_f=\frac{T_s\Omega}{T_s+\Omega^2} \tag{31}$$

Let

$$B=\frac{\Omega J}{T_e+\Omega k} \tag{32}$$

so that equation 30 can be written

$$\omega=\omega_f\left(1-e^{-\frac{t}{B}}\right) \tag{33}$$

Now as in equation 10

$$i=I_e\left(1-\frac{\omega}{\Omega}\right)$$

which becomes from equation 33

$$i=\frac{I_e}{\Omega}\left[\Omega-\omega_f\left(1-e^{-\frac{t}{B}}\right)\right] \tag{34}$$

The watt-seconds generated in the resistor R_1 in the time t_1 is

$$E=\int_0^{t_1} i^2R_1dt=\frac{I_e^2R_1}{\Omega_2}\times \int_0^{t_1}\left[\Omega-\omega_f\left(1-e^{-\frac{t}{B}}\right)\right]^2dt \tag{35}$$

which becomes

$$E=\frac{I_e^2R_1}{\Omega^2}\left[(\Omega-\omega_f)^2t_1+B(2\omega_f)(\Omega-\omega_f)\times\left(1-e^{-\frac{t_1}{B}}\right)+\frac{\omega_f^2}{2}\left(1-e^{-\frac{2t_1}{B}}\right)\right] \tag{36}$$

Let

$$t_1=\frac{2\Omega J}{T_e+\Omega k}=2B \tag{37}$$

so that

$$\omega_1=\omega_f(1-e^{-2})=0.865\omega_f$$

Let

$$d=\frac{\omega_f}{\Omega} \tag{38}$$

so that from equation 31

$$\frac{\omega_f}{\Omega}=d=\frac{T_e}{T_e+\Omega k} \tag{39}$$

Then from equation 37

$$B=\frac{\Omega J}{T_e+\Omega k}=\frac{d\Omega J}{T_e} \tag{40}$$

Substituting equation 38 and equation 40 into equation 36 gives

$$E=I_e^2R_1[2(1-d)^2+2d(1-d)(0.865)+0.491d^2]\frac{d\Omega J}{T_e}$$

which, using equation 9, reduces to

$$E=J\Omega^2\frac{R_1}{R}[2-2.27d+0.761d^2]d \tag{41}$$

Example 1

A centrifugal casting machine used for spinning molten metal to desired shapes is driven by a five-horsepower 230-volt 1,200-rpm d-c shunt motor with a full-load current of 20 amperes. The inertia referred to the motor shaft is 20 pounds feet squared. The load during acceleration is practically all friction and is ten per cent of rated full-load torque. A two-point starter with one section of starting resistance is to be used. In order to make the accelerating time short 200-per-cent starting torque is indicated.

The accelerating time setting for the timing relay and the watt-seconds lost per start in the starting resistor are required.

The rated full-load torque is 5(5,250) ÷ 1,200 = 21.9 foot-pounds, so that the initial torque and load torque are 43.8 and 2.19 foot-pounds respectively. Since the rated motor speed is 1,200 rpm, and the speed regulation or internal resistance drop is assumed to be ten per cent, the no-load speed is 1,333 rpm. From Figure 4a where $T_L = 0.1\ T_{FL}$ the switching speed is 0.82 × 1,333 or 1,093 rpm, and the steady-state speed, ω_f is 1,266 rpm. The time constant $\Omega J/T_e$, in the practical system, is given by the relation $(WR^2N) \div (307.8T_e)$ where WR^2 is in pounds foot squared, N is no-load revolutions per minute, and T_e is initial torque in foot-pounds. Inserting the values WR^2, N, and T_e given in this example gives the time constant of the system as 2.0 seconds. In a time of 1, 2, 3, and 4 time constants the speed will be 63.2, 86.5, 95, and 98 per cent of ω_f and the watt-seconds lost in the resistor will be 5,920, 6,950, 7,160, and 7,220.

If switching occurs at two time constants, the second current peak is given by equation 25 or can be obtained graphically from a construction similar to Figure 2. This current peak equals

$$I_1=\frac{V}{r}\left[1-0.865\frac{\omega_f}{\Omega}\right]=\frac{230}{1.15}\left[1-0.865\left(\frac{1,266}{1,333}\right)\right]=36.0\text{ amperes}$$

This inrush is allowable, being less than 200-per-cent full-load current, so that

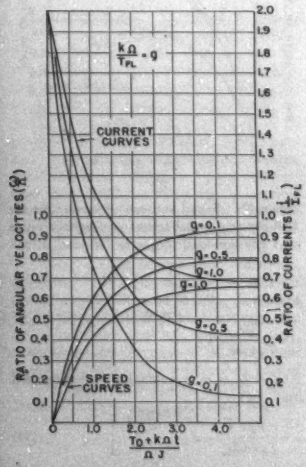

Figure 5a. Speed and current versus time for 200-per-cent initial torque and various ratios of load torque to full-load torque when the load torque varies directly as the speed

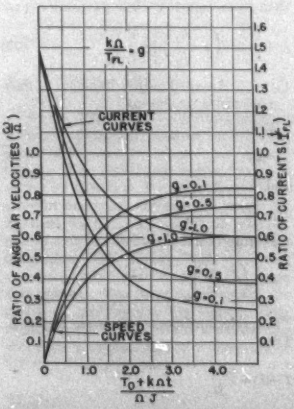

Figure 5b. Speed and current versus time for 150-per-cent initial torque and various ratios of load torque to full-load torque when the load torque varies directly with the speed

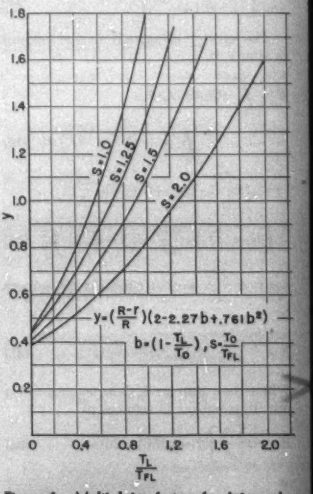

Figure 6. Multiplying factors for $J\Omega^2$ to obtain watt-seconds dissipated in resistor per start for various ratios of initial torque to full-load torque when the load torque is constant and switching occurs at a time equal to two time constants

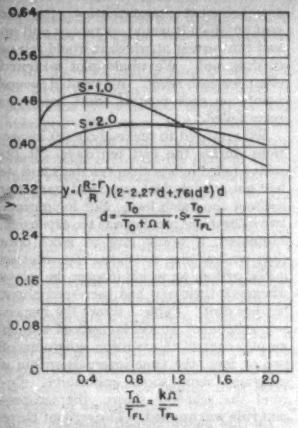

Figure 7. Multiplying factor for $J\Omega^2$ to obtain watt-seconds dissipated in resistor per start for various ratios of initial torque to full-load torque, when the load torque varies directly with the speed and switching occurs at a time equal to two time constants

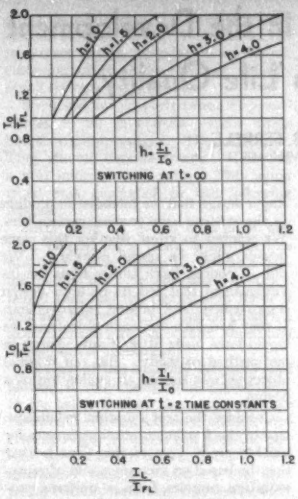

Figure 8. Curves showing the relation between first and second current peaks as a function of load torque, initial torque, and switching time

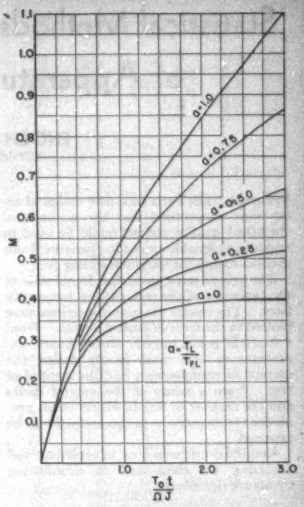

Figure 9. Multiplying factor for $J\Omega^2$ to obtain watt-seconds dissipated in resistor per start as a function of switching time for various ratios of load torque to full-load torque for a constant-torque load

Plotted for 200-per-cent initial torque

switching at two time constants or four seconds is satisfactory.

Example 2

A five-horsepower planer motor rated 500 rpm, 230 volts with a full-load current of 20 amperes drives a friction load of 25-per-cent full-load torque. If a two-point starter is used, the switching time and watt-seconds in the starting resistor are to be determined.

The WR^2 of the system referred to the motor shaft is ten pounds feet squared. The full-load torque is 52.5 foot-pounds. If 200-per-cent starting torque is allowed $T_0 = 105$ pounds. The no-load speed is 556 rpm. Then the time constant becomes $\frac{10\ (556)}{307.8\ (105)} = 0.172$ second.

The $J\Omega^2$ of the system is

$$\frac{4.62(WR^2)(N^2)}{10^4} = \frac{4.62(10)(556)^2}{10^4}$$

$$= 1{,}430 \text{ watt-seconds}$$

At two time constants the second current peak from equation 26 is

$$I_1 = \frac{230}{1.15}\left[0.135 + 0.865\left(\frac{0.25}{2}\right)\right]$$

$$= 48.6 \text{ amperes}$$

The multiplying factor for $J\Omega^2$ obtained from Figure 6 is 0.475. Then the watt-seconds become $0.475 \times 1{,}430 = 685$ watt-seconds.

It should be noted that this value is approximately ten per cent of the value found for the motor of example one, which has the same applied voltage, horsepower, internal resistance, and inrush current.

The watt-seconds per start are not much different for two, three, or four time constant because of the low-load torque. If a high-load torque is present, a two-point starter is not satisfactory because of the high resultant second peak.

Appendix. Nomenclature and Units

e = counter electromotive force at any instant
e_1 = value of e at time t_1
V = line voltage
i = armature current at any instant
I_0 = armature current at $t = 0$
I_1 = armature current after switching time $t = t_1$
I_L = current corresponding to torque T_L
R = total resistance in armature circuit
R_1 = external (starting) resistance
r = internal resistance of motor
T = torque developed by motor in watt-seconds
T_0 = value of T at $t = 0$
T_L = constant load torque in watt-seconds
T_1 = variable load torque at any speed in watt-seconds
T_Ω = value of T_1 at speed of Ω
KE = kinetic energy of rotating system in centimeter-gram-second units
J = polar moment of inertia of rotating system in centimeter-gram-second units
WR^2 = inertia in pounds feet squared
E = energy in watt-seconds
ω = angular velocity at any instant in radians per second
ω_1 = value of ω at $t = t_1$
ω_f = value of ω at $t = \infty$
Ω = no-load angular velocity in radians per second
N = speed in revolutions per minute
α = angular acceleration at any instant in radians per second squared
t = time in seconds
t_1 = value at t at $\omega = \omega_1$
ϕ = useful flux per pole crossing the air gap
k = constant
A, C = constants of integration
$b = (T_0 - T_L)/T_0$
$d = T_0/(T_0 + \Omega k) = \omega_f/\Omega$

In order to change from metric units to the practical system the following factors can be used.

$$\frac{WR^2}{32.2} \times 1.358 = J \text{ watt-second}^2$$

$$4.62WR^2N^2 10^{-4} = J\Omega^2 \text{ watt-seconds}$$

$$\frac{2\pi N}{60} = \Omega \text{ radians per second}$$

Statistical Methods in the Development of Apparatus Life Quality

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Synopsis: Life tests on a new design of relay were so planned that the methods of statistical quality control could be used to separate assignable causes for variation from random causes for variation during life.

The relays were inspected frequently at the beginning of the test and less frequently later. The results of these inspections were plotted in the form of control charts. From a study of points outside control limits, improvements were made in the design, the method of manufacture, and the method of test. From a study of the control limits and the number of points within them, predictions were made as to the useful life to be expected.

Simplified methods used in recording and analyzing the data and in establishing trends are described.

DEVELOPMENT PEOPLE, manufacturers, even consumers, make a great many life tests. A common way of making these life tests is something like this: Go to the end of the assembly line, get a number of whatever kind of gadget is being made, put them in a life-test station, and run them to destruction. Results: A nice table of numbers and a lot of dead gadgets. Nothing more.

Now, what is the purpose of a life test? The consumer wants to know: How often will I have to replace this piece of equipment? The manufacturer or his development man wants to know: How long a life can we guarantee to our customer?

The very nature of these questions shows that they are not at all interested in how long a particular gadget that was made last month did run before failure. They are interested only in predictions about how long many gadgets that will be made next month will run before failure. To restate the questions to be answered: First, can reliable predictions be made about the life of the gadget? Second, if predictions can be made, what are the expected average and dispersion of the life, or, if reliable predictions cannot be made, why not, and what can be done about it?

There is another question: Can a design change be made that will increase the life or reduce the cost? That question was given little consideration in setting up the tests to be described, because we had a design that we intended to produce in the existing form to meet certain uses. We wanted to know whether this same design might be useful elsewhere. We did, of course, learn things from the investigations that led us to both design improvement and process improvement. If they had been our main objectives, we would have made little, if any, change in our method of study. But our original objective was simply an evaluation of a design.

Consider the first question, reliability. One of the fundamental requirements for reliable predictions of this type is that they be based on measurements of representative samples from a uniform product. In the tests to be described here the product to be studied was a new type of relay which was in the midst of development and preparation for manufacture. We had made a good many small lots. We had studied the more important characteristics of these by the control-chart technique.[1,2] We had some confidence in a process standard that had been based on our control limits. We were getting a good many outages in our manufacturing process. That is, we were getting a good many points outside our control limits. But we were identifying and eliminating the troubles. Another way to say this is that we were making a good many relays that were not what we intended, but we knew what we wanted to make, and we knew a process that would do it.

For the life test we took samples from those lots which were in statistical control. We believed our samples were representative of the stable manufacturing process that would exist after we had eliminated the troubles. And we knew what the characteristics of the relays made by that process would be, knew that they would be useful to our customers.

We believed that, if we were to put much faith in an ultimate life figure, it must be arrived at by a more or less continuous and understandable process. That is, we were not satisfied merely to let these relays die; we wanted to know how they aged and what was the nature of their final failure. We arranged to operate and release each relay in a work circuit 60 times per second in an effort to wear it out. At stated intervals we would remove it from this work circuit and inspect it. This inspection would consist of accurate measurements of its two principal characteristics: the current at which it would operate or pull up, and the current at which it would release or drop out. We would plot a control chart for each relay. We wanted several points on each control chart before its relay failed.

We arranged to make about 20 inspections during the first ten days. If the relays failed in less than ten days and we had not enough data, we could start over without too much loss. But to continue two inspections per day was too expensive. Moreover, it would give us more data than we had time to study. So, after an initial period, we would inspect the relays whenever their age had increased about ten per cent. Table I shows the inspection schedule. It will be noticed that, if we plot control charts using subgroups of two or four, the time intervals within a subgroup show some uniformity. Beyond the schedule shown, the ten-per-cent rule was applied. Throughout there was some adjustment to fit convenient working hours.

In measuring the operate and release current at the inspections, we have used a measuring set that minimizes the influence of the operator or the surroundings. The relay is connected to the measuring set, and the operating switch is thrown. The measuring set automatically increases the current in the relay slowly until it operates and then displays the value of the operate current on a meter for several seconds. The operator merely throws the switch, reads the meter, and writes down the reading. The meter has a six-inch scale and is read to one or two parts in 1,500.

Table II shows the method of recording the data. This is one half of a double page. Release current is recorded on the other half. There is a separate double page for each relay. At each inspection four observations of operate current are made and recorded on one line. After them are recorded the range and midrange of these four repetitive observations. They may be called repetition range and repetition midrange. When two inspections have been made, the two

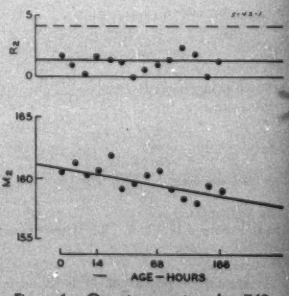

Figure 1. Operate current: relay 740

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repetition midranges are treated as new data, and the range and midrange are computed for the group of two.

In this work and in most of our work we have used ranges and midranges in preference to standard deviations and averages. The ranges and midranges are easier to compute, and the method of computing them is exactly the same in all details, whether the sample size is two or six. This simplifies the instructions to the technical assistants and speeds up their work. As these statistics depend on only the extreme observations, they may be a little more useful in detecting trouble. Control chart coefficients are published for ranges. For a sample size of two, the midrange and average are, of course, the same. For small samples, in general, it may be that the midranges and the averages, with their statistical fluctuations, are enough alike to permit their interchange in an analysis of this type. We have assumed this to be so, and up to sample sizes of six, we have used the midrange with the published control-chart coefficients for the average.

Repetition ranges represent variations in the relay, and also variations due to meter reading, building vibration, and the like. We would expect this dispersion to be constant, both within and among the relays. The average repetition range and control limits based on it were computed by lumping together several inspections on several relays. They are shown at the bottom of Table II. The repetition ranges here are badly out of control. This was at the beginning of the tests. We convinced ourselves that the trouble was due to operator inexperience and was not seriously affecting the experiment. The repetition ranges later did come into fairly good control.

The group ranges represent the aforementioned variations plus the variations caused by handling the relays, drifts in the measuring set and the like, plus any variation due to real aging in the relay. They show, on the whole, very good control. They indicate that the effect of aging between inspections is small as compared with what we might call the effect of handling.

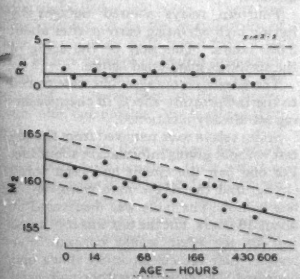

Figure 2. Operate current: relay 740

We do not expect the repetition midranges to stay within limits based on repetition ranges, because an additional cause for variation, the handling, is interposed between inspections.

We might have expected the group midranges to be in control within limits based on group ranges. They were not. They showed definite trends. Here was a real indication of aging. This aging trend was evaluated in the following manner.

After some 14 group midranges had been plotted for a relay, a median line was drawn as in Figure 1. It was a sloping median line. It was placed at such a height that half the points were above it and half below. It was placed at such a slope that the number of runs, above and below, was a maximum.

The use of this line and the method of placing it may need some explanation. If we believed that there existed some functional relation between operate current and age, we could compute the current for each age on the basis of that functional relation, subtract the computed current from the observed current, and get a set of remainders. These remainders would represent the departure of our experience from the assumed functional relation. We could study these remainders statistically. If we found, in the remainders, evidence of cycles or trends, then we would say there are functional relations other than that already considered. If we found what the statistician calls "no evidence of lack of control," then we would think there is no functional relation between the remainders and the age. Our confidence in this belief would depend on the thoroughness of our search for lack of control.

We have done just this, but have done it graphically. We have used, in effect, a graphical transformation of co-ordinates. The functional relation that we have used is defined by the time scale, the position, the slope, and the straightness of the line. Because we have an unusual time scale, we are testing an unusual functional relation. There may be a better or more logical functional relation. The best of statistical control in the remainders would not prove that this functional relation is "the right one" but merely that empirically it is a good approximation in the region studied.

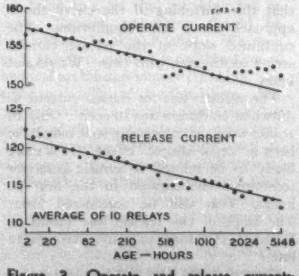

Figure 3. Operate and release currents: average of ten relays

Table I. Life-Test Inspection Schedule

Number of Inspection	Age in Hours	Added Age	Number of Days	Number of Groups (2)	Number of Groups (4)
1*	0				
2**	0	0		1	
3	1	1			
4	2	1	1	2	1
5	5	3			
6	8	3	2	3	
7	11	3			
8	14	3	3	4	2
9	17	3			
10	20	3	4	5	
11	23	3			
12	26	3	5	6	3
13	33	7			
14	40	7	6	7	
15	47	7			
16	54	7	7	8	4
17	61	7			
18	68	7	8	9	
19	75	7			
20	82	7	9	10	5
21	89	7			
22	103	14	10	11	
23	110	7			
24	124	14	11	12	6
25	131	7			
26	145	14	12	13	
27	152	7			
28	166	14	13	14	7
29	188	22	14		
30	210	22	15	15	
31	232	22	16		
32	254	22	17	16	8
33	276	22	18		
34	298	22	19	17	
35	320	22	20		
36	342	22	21	18	9

*At completion of manufacture.
**At start of life test.

In our case the time scale and straightness of the line were purely matters of convenience. They fixed the form of a two-parameter function whose two parameters, the height and slope of the line, could be easily chosen. The choice of height rests on our desire to have the central value of the remainders after transformation equal to zero. It is somewhat easier to use the median as the measure of central value than some of the others. So, we placed the line with half the points above and half below.

We have chosen the slope of the line in an effort to make one of the simplest tests for control show no assignable causes. This test is the study of runs[3] above and below the median. A run is a sequence of consecutive points on the same side of the line. The expected number of runs is roughly half the number of points, actually $(n+2)/2$. This makes the expected average length of run about two. The presence of longer and fewer runs tends to indicate the presence of trends. We would like to include any such trends in our functional relation, and that would eliminate those long runs. The presence of shorter and more numerous runs, which

Table II. Life-Test Data

NI$_{80}$ Switch 740

Date	Age	Observations				Repetition R_4	Repetition M_4	Group R_5	Group M_5
713	0	159.8	160.1	159.9	160.1	0.3	160.0		
806	0	160.3	160.2	163.8	160.0	3.8	161.9	1.9	160.9
	1	162.[illegible]	161.9	162.0	162.0	0.1	162.0		
807	2	161.9	160.2	161.8	160.0	1.9	161.0	1.0	161.5
	5	160.1	160.0	160.8	160.1	0.8	160.4		
	8	160.4	159.8	160.5	159.9	0.7	160.2	0.2	160.3
809	11	160.2	159.7	160.2	159.8	0.5	160.0		
	14	162.0	161.7	162.0	161.9	0.3	161.9	1.9	160.9
810	17	161.9	161.0	161.9	161.5	0.9	161.5		
	20	162.5	162.4	163.1	162.4	0.7	162.7	1.2	162.1
811	23	159.9	160.0	159.9	159.8	0.2	159.8		
	26	158.3	159.0	158.8	159.0	0.7	158.7	1.1	159.2
812	33	158.0	160.0	160.5	160.0	1.5	159.8		
813	40	159.8	159.9	159.8	159.9	0.1	159.8	0.0	159.8
	47	160.0	160.0	160.0	160.0	0.0	160.0		
814	54	161.0	160.2	161.0	160.2	0.8	160.6	0.6	160.3
816	61	160.0	160.2	160.5	160.5	0.5	160.3		
	68	161.0	161.8	161.5	161.5	0.8	161.4	1.1	160.8
817	75	160.5	159.8	161.0	159.9	1.2	160.4		
818	82	158.5	158.5	159.0	158.5	0.5	158.7	1.7	159.6
Process standard	Average					0.24	1.33		
	Limits					0	0		
						0.55	4.35		

means many runs of length one, indicates a cyclic variation with a period of two. That would not affect our choice of slope to represent a long trend. So, we have used that slope which gave the greatest number of runs.

These ideas explain, whether or not they justify, our method of drawing this line, which because of its characteristics we call a median line. Because this is an extension of the original concept of the median of a lumped or unordered distribution to the concept of a median of an ordered array, we have qualified it and called it a sloping median. Perhaps trend median would be a better name.

These sloping median lines were drawn for eight relays with encouraging results. The number of runs was fairly close to the expected number. The slopes were in good agreement. To show this we measured and averaged these slopes and redrew the plotted medians, so that all had this average slope. Since the manufacturing variations among relays is greater than any of the variations discussed here, each line was drawn at a height to make it the median for that one relay.

To study further the singleness of this assignable cause for variation, control limits were placed above and below these median lines at spacings derived in the usual manner from the average group range. Figure 2 shows the complete control chart for group range and midrange.

Note that this chart goes up to 600 hours age. The determination of slopes and control limits was made on eight relays at an age of 166 hours. The control chart is holding good through an extrapolation by a factor of nearly four in age.

Figure 3 shows the aging trend up to 5,000 hours. The upper curve is for operate current, the lower for release current. Each point is the average for ten relays. It represents four repetitive readings, at each of two inspections of each of ten relays—a total of 80 observations, averaged in each point. The slope of the median line for operate current is the same as that determined at an age of 166 hours. The last few points are significantly above the line. It may be that the whole aging trend is caused by change in a repeatedly overstressed spring and that this flattening of the curve shows approach to a new equilibrium. The continued slope of the release current seems to disagree with this. We do not know.

The median line for release current as drawn at 166 hours was steeper. Only 14 points were available then, so it may have been a "small sample" effect. It is more likely to be related to erratic behavior sometimes encountered in the first 20 hours. This will be considered later. The slope of the release line shown in Figure 3 is the same as that of the operate line.

Control limits have not been drawn on the ten relay average curves of Figure 3. If they were, they would be spaced less than a third as far apart as in Figure 2, and we would observe many outages. We think the explanation is this: In addition to the dispersion due to what we called "handling," there is an effect of temperature on the measuring set. This is less than the "handling" effect, and, in single relays, is concealed by it. When we average ten relays, the dispersion due to handling is reduced. But, because the relays were started into their tests in a few groups and measured together later as a group on a cold day or a hot day, averaging does not reduce the temperature effect. This now shows up to give outages on limits set by the "handling" dispersion. This also will be mentioned again. This same temperature effect probably accounts for some of the long runs observed in the individual curves.

At the beginning of this discussion two questions were asked: What prediction? How reliable? A prediction has been obtained: A life of over 5,000 hours with an aging in that life of nine parts in 150. For reliability it is necessary to return to our control charts.

Table III is a summary of outages observed in tests on 28 relays. At the time of preparing this summary, some had been run to destruction, others had been run a few hundred hours without failure, and others a few thousand hours.

Table III. Summary of Outages

Number of Relays	Identification	Action
All	General trend	New spring
9	Initial	Preage product
10	Measuring set	Repair set
14	Spring stabilisation	New spring
6	Temperature	Redesign measuring set
7	Faulty test	Start over
	Faulty manufacture	Modify process
3	Heavy load	Study load circuits
10*	Unexplained	No action

*Number of individual points outside control limits

Nine relays showed outages in the first 20 hours, mainly high values. The time scale used was that of the schedule of Table I. If the chart is replotted on other time scales, some of these outages disappear, and others appear. We do not know what time scale should be used. It may not be important. We think these early outages indicate a real trouble and contributed to our bad guess on the aging rate for release current at 166 hours. There is still more to be said about this.

Ten relays showed outages all at about the same time when the measuring set went bad. That trouble was corrected. It was found that the calibration of the set had been in error by about two per cent. In the plotting of these charts, the early points have been corrected by that amount.

Fourteen relays showed outages by having high operating current after about 2,000 hours. This may be the aging of the spring as mentioned before.

There were six outages that were traced to the temperature effects in the measuring set already mentioned.

Seven relays were removed from the life test without giving information about life. For one pair the circuit had been wired wrong, and the relays were worn out in 600 hours. The fault was discovered at about 40 hours, but the test was continued just to see what would happen. For another pair the circuit broke down and damaged the relays. Another pair aged very rapidly and was found to have been

Selsyn Design and Application

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IN the last few years, new developments of Selsyn principles and new applications of modified designs have opened a vast field of use, the emphasis of which is on the system, within which the Selsyns exert control. The many advantages of these new uses are not yet fully realized. Therefore an explanation of the fundamentals of design and application of Selsyns will give a firmer basis for present applications and increase the future usefulness of this highly versatile means of control.

In certain forms Selsyns have had a reasonably long and distinguished service in industry in the past in such applications as remote indication of water level, controller position, and so forth. Many improvements have been made, and much has been learned about the possibilities and limitations of such systems. This paper presents a discussion of design and application fundamentals as distinguished from the mathematical analysis.

What Is a Selsyn

Selsyns, as discussed in this paper, are electric machines used as control devices which in systems involving two or more units can indicate the relative position of their shafts to a high degree of accuracy, even though a considerable distance may intervene between the units (the name is a contraction of self-synchronous). A servo mechanism, or servo system, is an arrangement of power and power-control units within which the Selsyn system operates to guide the action of the power units.

The different kinds of Selsyns can be classified roughly by size and accuracy as:

1. Power Selsyns.
2. Instrument Selsyns.
3. Indicator and control Selsyns.

Power Selsyns are similar in construction to wound-rotor induction motors and have an equivalent size. They might be used, for example, to maintain synchronism of the ends of a lift bridge. Instrument Selsyns are usually extremely small and light and used only to carry a light-weight pointer to indicate position, for example, of the trim tabs or wheels in an airplane. Extreme accuracy is not required of either of the foregoing kinds of Selsyns. Indicator and control Selsyns are midway in size and have errors counted only in tenths of degrees. Because of their high accuracy as control devices they enjoy a much wider field of use than either of the other two types.

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Basic Selsyn Systems

An explanation of elementary Selsyn systems is needed as a basis for design specifications. Selsyn systems may be divided into two basic groups, depending on whether their principle of operation is

1. Torque transmission

or

2. Voltage indication.

Each type of system has its own unique advantages, depending on the needs of

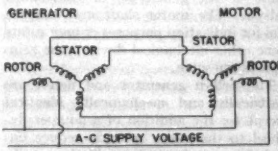

Figure 1. Selsyn generator and motor connection diagram

improperly made. The seventh failed suddenly at 2,690 hours and was found to have a foreign particle in it that had worked into the hinge. This also was faulty manufacture. These seven told us nothing about normal relays.

Three relays operated at heavier loads have failed. The ten relays used to plot the average aging curve were worked into loads of 20 watts or less. One of these three relays was worked at 200 watts. It shows a normal aging curve but failed at 2,645 hours. The other two were worked at 300 watts. They showed abnormal aging and failed at 490 hours. There was some question as to the manufacture of these two as they were taken from a lot with a large number of known defectives. From this meager information we are tempted to guess that at these heavy loads the dependable life is about 500 hours.

In addition to these outages for which causes have been assigned, there were ten outages in over 2,000 points for which the cause is unknown. With three sigma limits, the expected number of outages is six, and the sampling fluctuations might take this up to 13. It is possible that these ten outages are really due to random fluctuations.

From these tests we have two sets of conclusions to draw. For the consumer, we can promise a useful life of over 5,000 hours at 60 operations per second with a load of 20 watts or less in a properly designed circuit. At 200 or 300 watts, we have some indication of a life of a few hundred hours. This applies to relays made by the standard process as it existed at the time of the test.

For the development man we have several conclusions. First, we need a measuring set that is easier to operate and free from temperature effects. We are now building a set that we think will be better. Second, something should be done about the initial aging. We now think this is caused by a combination of chemical action and impact polishing. It seems to stabilize after a few hours. We have introduced a stabilization aging run as part of the manufacturing procedure. Third, the aging trend, though small as relay aging usually goes, is undesirable. We should note that the very fact that we had to draw our control charts on sloping medians indicates the presence of an assignable cause. We traced this to the over-stressed spring; we changed the spring material, and new tests indicate that we have almost eliminated this slope. Fourth, the relays were damaged by heavy loads in the circuit used. This may be because of the load and hence an inherent limitation, or it may be because of the circuit which is now being studied.

This report may be summarized this way: The life tests were so designed that random causes and assignable causes could be separated. From the data related to the random causes we have made predictions about the useful life of our standard product in which we have much confidence. From the data related to the assignable causes we have been led to improvements in our design, our manufacturing process, and our testing process, and we may be led to improvements in our method of use.

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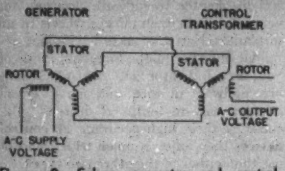


Figure 2. Selsyn generator and control-transformer connection diagram

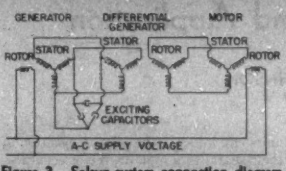


Figure 3. Selsyn-system connection diagram including differential Selsyn and exciting capacitors

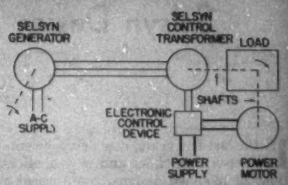


Figure 5. Connection diagram for typical servo system

the application. In some cases a group of interconnected Selsyns forms a system of its own, but more generally it is only part of a larger servo system which it controls.

Selsyn Generator and Motor System (Torque Transmission)

The first basic type of system comprises two Selsyns between which torque is transmitted electrically to rotate the shaft of the motor, or receiver Selsyn, in synchronous correspondence with the shaft of the generator, or transmitter Selsyn. The motor shaft may carry a dial for indication purposes or may rotate some other mechanical device; the principle is the same.

The Selsyn generator and motor are electrically and mechanically identical except for the addition of a damper flywheel to the motor rotor to reduce undesirable mechanical oscillations. In each excitation power is applied to a single-phase primary (usually rotor) winding which induces voltages by transformer action in the three secondary (usually stator) windings which are connected in the conventional Y with 120-degree mechanical spacing.

When the stator windings are interconnected as in Figure 1, any lack of correspondence between generator and motor rotors causes the voltages in the stator windings to become unequal, thus circulating currents through the windings and producing restoring torques to bring the motor into correspondence with the generator. When both rotors are in correspondence, the stator voltages are equal, and no current flows.

The voltages induced in the stator windings are all in time phase, since only single-phase power is applied to the rotor and the Selsyn revolves only slowly. The magnitudes of the various voltages depend on the relative postion of stator and rotor windings, and thus a unique set of voltages is produced in the stator for each position of the rotor. The fact that these sets of voltages are a very accurate measure of rotor position is responsible for the widespread use of Selsyn systems.

Selsyn-Generator and Control-Transformer System (Voltage Indication)

The second basic type of system comprises two Selsyns connected electrically, in the second of which (the control transformer) a voltage is induced whose polarity and magnitude are functions of the relative direction and amount of displacement between the shafts of the two units. This voltage can be used for indication purposes but generally acts as control voltage for a servo system.

The Selsyn generator of this system is identical in all respects to that of the first basic system described. The Selsyn control transformer is similar to the generator, except that it has a high-impedance winding on the stator and the rotor winding is not connected to the power supply.

When stator windings of generator and control transformer are interconnected as in Figure 2, the currents in the control-transformer winding are proportional to the voltages in the generator windings, thus producing a magnetic field in the control transformer corresponding to that in the generator. The voltage induced in the single-phase winding of the control transformer is thus a sine function of the relative displacement of the rotors.

Modification of Basic Systems

A differential Selsyn may be included in either basic system. It functions either as a differential generator to transmit a set of Selsyn voltages, while modifying them by adding or subtracting the amount of rotation of its shaft, or as a differential motor to receive voltages from two generators and rotate the sum or difference of their rotations. The voltages applied to the three-phase primary (usually stator) windings of a differential generator from the Selsyn generator induce a new set of voltages in the secondary three-phase windings, which appear as if the generator has been turned additionally by the amount of shaft rotation of the differential. An exciting capacity in parallel with the primary winding of a differential Selsyn often is used to reduce the heating of the rest of the system. Figure 3 illustrates a typical connection diagram for a Selsyn system, including a differential generator.

Figure 4. View of indicator panel for bascule bridge showing Selsyn-operated indicators

Typical Selsyn Applications

To illustrate the basic systems just described, some typical applications of Selsyn systems are helpful.

Selsyn Generator–Motor System as Position Indicator

The leaves of a bascule bridge must be kept closely synchronized in position to insure correct operation. Automatic equipment is provided to accomplish this, but Selsyn systems often are used to provide visual proof to the operator that all is well.[1] A Selsyn generator is geared to each leaf of the bridge, and the shafts of corresponding Selsyn motors are attached to pointers on a dial to represent the bridge. The pointers correspond accurately to the position of the leaves and thus quickly check operations. Figure 4 shows the dial of such an installation. Figure 1 shows the connection diagram for the installation.

Similar applications of Selsyn systems were made as early as 1914 to show the position of lock gates, safety chains, and water levels in the Panama Canal.[2]

Selsyn Generator–Motor System Used for Transmitting Torque

Continued rotation of a Selsyn generator will cause rotation of the connected Selsyn motor, whose shaft will rotate any attached load up to the limit of the allowable transmitted torque. This flexible-shaft operation of Selsyns is similar in all respects to the previous example, except that an average angular difference between generator and motor is required to supply load torque.

This use of Selsyns is obviously very convenient in many cases but has definite limitations in the amount of torque that can be transmitted without overheating the system and in the mechanical oscillations that may occur with changes in load. A better system is described in the following paragraphs.

Selsyn-Generator–Control-Transformer System Controlling Typical Servo System

Torque amplification, or the control of a large or high-power object by means of a small or low-power one is often necessary in industry (for example, in the machine-tool trade). Many new developments, and therefore the greatest possibilities, are in a system utilizing the high accuracy of control of a servo system possible with a Selsyn-generator–control-transformer system. A typical servo system is diagrammed in Figure 5.

The output voltage of the control transformer (which is proportional to the relative position of generator and control transformer) is fed to an electronic control device, which controls the flow of power to the driving motor. The driving motor turns the load (and control transformer) until the output voltage of the control transformer becomes zero. Any motion of the generator results in a corresponding motion of the load with an accuracy independent of the size of the load, as the driving motor is chosen accordingly. This is a new type of application for Selsyns and bids fair to eclipse all others in versatility of usefulness. A great amount of development has been done designing electronic control devices for maximum performance for each application. Their design is highly important to successful system operation but is outside the scope of this paper.

Characteristics, Design, and Construction of Selsyns

The use specifies the operating characteristics of a machine, and these in turn determine the design and method of construction. Selsyn systems of the first basic type have been in operation for some time, although the use of both types has been rapidly broadening in the last few years. Consequently, many present standard types of construction and methods of design have evolved from other machines such as small a-c synchronous motors. From a study of the requirements of each kind of Selsyn the most suitable design may be evolved.

Selsyn Generator

For a generator used in either of the basic Selsyn systems, the general specifications are about the same.

1. Secondary voltages are such functions of rotor position that a highly accurate indication of position can be obtained when operated with a complementary Selsyn.

2. Sufficient torque developed when coupled with a suitable Selsyn motor, so that motor friction, or the resistance of a specified connected load, may be overcome sufficiently for required accuracy.

3. Minimum drain of current and power from supply lines when operated at rated voltage and frequency.

Table I. Torque Gradients

Values Are for 60 Cycles

Model*	Inch-Ounces Per Degree	Model	Inch-Ounces Per Degree
1	0.07	2	0.16
3	0.45	4	0.40
5	1.2	6	1.75
7	3.4		

* See Figure 9 for relative sizes of units.

4. Adequately large torque capacity and low-voltage regulation to give proper performance of the rated number of connected Selsyns in specified systems.

5. A temperature rise under operating conditions adequate to insure satisfactory life.

6. Bearing design and lubrication suitable for high position accuracy and adequate life at specified rotation speeds and temperatures. Allowance must be made for possible limitations in available torque from the driving device.

7. Construction must include convenient means of mounting and resistance to normal hazards of operation such as vibration, shock, moisture, dust, fungus, and so forth.

The design of a Selsyn generator is like that of any small a-c machine, and the construction is often similar. A standard type of construction of stator and rotor for a generator is shown at the left in Figure 6. All circuit quantities and methods necessary to make standard analyses of Selsyns and their circuits are contained in the usual analysis of synchronous a-c machines.[4] Unfortunately, since Selsyn errors are caused by deviations from the approximate theory commonly used, there is as yet no precise method of predicting error or designing for a given controlled amount of it. The usual design formulas for larger synchronous machines can be used for excitation and torque calculations on all types of Selsyns, if correction is made for the changes in relative dimensions. Ordinary precautions regarding distribution of the coils of the winding, number and skew of slots, and so forth must be taken, but special precautions are needed on machining tolerances, if accuracy is to be high.

Most Selsyns have a sinusoidal variation of stator line voltage with rotor position. Figure 7 shows the variation of the magnitude of the three line voltages. All voltages are in time phase. It has been shown that any space harmonics in the flux distribution, caused by the location of coils or dissymmetry of the magnetic structure, and time-phase differences between current in the various windings, caused by any circuit unbalance, can produce errors in the Selsyn system. The collector rings and brushes must be of durable materials with low stable voltage drop to avoid erratic errors. Gold or silver alloys are commonly used.

The torque developed by a pair of Selsyns (except control transformers) when their rotors are out of correspondence varies with the sine of the relative angular difference as shown in Figure 8. The amount of this torque for a given design may be calculated in terms of the usual electric-machine-circuit constants.[3] Representative generators develop torque gradients with electrically identical motors as shown in Table I.

The models 1, 3, 5, 7 generally are used for position indication only, whereas models 2, 4, 6 are used alternatively for torque transmission as electrical flexible shafts.

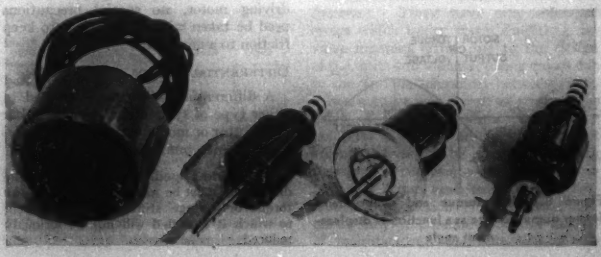
Since for normal operation Selsyns are at or near correspondence position, the circulating currents in the stator are relatively small; consequently, the excitation power is the principle factor in determining heating. A stiffer torque gradient therefore can be built into Selsyns which are intended for position-indication use only, resulting in increased torque to overcome bearing and brush friction and provide better accuracy.

Recommended system loadings of various sized generators are given in the next section. Accuracy and heating are the limiting factors.

Selsyn Motor

A motor is used only in the first of the basic systems—that utilizing torque transmission. As previously mentioned there are two possible uses of that system;[4] the motor shaft may carry a lightweight dial

Figure 6. Standard Selsyn construction showing stator, generator rotor, motor rotor with damper, and differential generator rotor



which, once set properly, records the position of the generator shaft very accurately, or the motor shaft may drive some device or load in synchronism with the generator shaft. The requirements are the same as for generators, but, in addition

1. The motor must come quickly into synchronism with the generator and not oscillate unduly when power is applied.

2. Bearing and brush friction must be kept low to insure a high accuracy of correspondence with the generator.

The design of all motor parts is identical with that of the generator in order to satisfy the general requirements of torque and accuracy, but in addition a damper is required. Oscillation of the motor is reduced by a mechanical inertia-friction damper fastened to the shaft, as shown in the middle rotor in Figure 6.

Special precautions must be taken with bearings for indicator Selsyns to insure low friction and high accuracy. All parts are cleaned carefully and aligned, and in critical cases special bearings are used. On the other hand Selsyns for torque transmission are inherently less accurate and in some cases may be built entirely from standard small induction-motor parts without special design.

Selsyn Control Transformer

A control transformer is used only in the second of the two basic systems—that using voltage indication. Its special requirements are:

1. The output voltage should be an accurate measure of the relative angle between generator and control transformer, and the power available should be sufficient to operate specified electronic devices.

2. The excitation power and current must be a minimum, as they must flow through the generator and therefore limit the number of control transformers that can be connected.

3. The reaction of a control transformer on the generator must not affect seriously the accuracy of transmission of position information to other control transformers that may be connected to the generator.

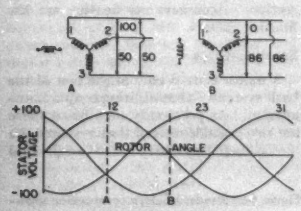


Figure 7. Selsyn-stator line voltages as a function of rotor angle

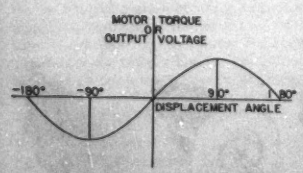


Figure 8. Motor-torque and control-transformer output voltage as a function of displacement angle

The mechanical design of a control transformer is similar to that of a generator. The variation of the output voltage with rotor position is sinusoidal as shown in Figure 8. To minimize the reaction of the control transformer on the generator the magnetic circuit is kept symmetrical by carefully shaping the rotor as shown in Figure 10 and using a three-phase stator winding similar to that on the generator but of much higher impedance. Thus only an equalized three-phase load is presented, the generator signal is not unbalanced, and the excitation power required is kept low.

The volt-ampere burden of electronic devices operated by the control transformer is commonly low, making easy the fulfillment of the requirements. However, if the load consists of peaking transformers for operating thyratron circuits, the volt-ampere burden is high, and a compromise is necessary with the requirement for low power drain from the generator, or excessive voltage regulation will be present.

Because the control transformer produces practically no torque and its shaft always will be positioned by some external driving motor, no special precautions need be taken with the bearings to keep friction to a minimum.

Differential Selsyn

A differential Selsyn may be used in either type of system and may be either a generator or motor with similar general requirements, but in addition

1. The series impedance introduced by the differential must be low enough, so that the torque or voltage stiffness of the system to which it is added will not be seriously reduced.

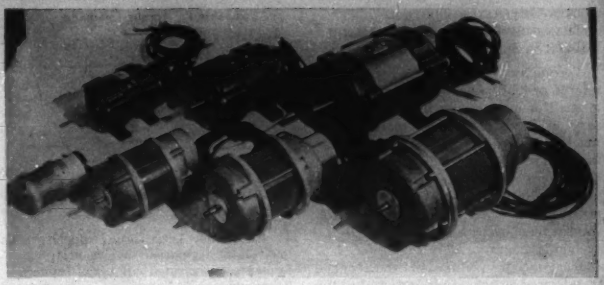


Figure 9. Standard Selsyn sizes

Left to right, front row: models 1, 3, 5, 7; back row: models 2, 4, 6

2. The excitation power and current requirements must be a minimum to reduce the heating of the generator.

The foregoing requirements require a compromise for best design. Usually a low-impedance design is aimed at, and then exciting capacity is placed in shunt with the primary winding to reduce the current drain load from the generator. The rotor at the right in Figure 6 is that for a Selsyn differential generator. The corresponding stator winding is practically identical with that of a generator.

Design Modification for Special Applications

The standard Selsyn designs just described can be built in all the variations of mounting, voltage, frequency, number of phases, and so forth of equivalent-sized standard induction motors. The fundamental Selsyn principle, however, can be applied in two special designs which are worthy of note here because of the flexibility of Selsyn application which they indicate.

Extremely small size may be obtained by a radical change in design to a Gramme ring type as shown in Figure 11. Here the stator winding is in the form of a toroid, while the rotor is of salient-pole design. This design lends itself to automatic machine winding in core and wire sizes impractical with conventional slotted stators. The principal disadvantages are that the impedance is inherently high and the design of a differential is quite awkward. The accuracy possible is quite comparable to that for larger standard units of the generator and control-transformer varieties.

For applications of limited rotation (±30 degrees), very high accuracy is sometimes made possible by winding the stators with only one phase, thus utilizing the winding volume and distribution to best advantage. The physical appearance

of such Selsyns may be identical with those previously shown, or stator and rotor may be mounted independently to occupy minimum space. The circuit in Figure 12 illustrates such an application.

The single-phase Selsyn units are identical and are operated as generators. The secondary voltages are connected opposing (for like rotation), and the difference voltage operates a servo system with one unit rotated by the sending mechanism and the other turned into synchronism by the servo-system power drive. Note the differences between Figures 12 and 5.

Possible Selsyn and Servo Systems

Selsyn systems of generators and motors for remote indication or generators and control transformers for controlling servo systems may consist of from 2 to 40 Selsyns or more. The problems of such systems are largely those of heating limitations in the generators and differential generators, since the accuracy is determined readily and the stability of the system is controlled by proper design of the electronic control device. Table II shows the number of motors and control transformers that can be handled by different sizes of generators without overheating. The model numbers refer to standard sizes and are not proportional to dimensions.

In general each proposed Selsyn system must be checked for heating experimentally as this method is much simpler and less fallible than usual calculations for small machines.

Accurate control of large amounts of power by simple and low-power means is the object of the design of a servo system.[6] A vast fund of knowledge has been acquired on the design of these systems during the last few years, and much of this data is yet to be applied industrially. An understanding of the principles of Selsyn control should hasten such applications. Servo systems controlled by Selsyns have been developed in a range from $^1/_{200}$ horsepower to 65 horsepower (there is no apparent upper limit).

Table II. Motor and Control Transformers Handled by Generators

Values Are for 60-Cycle Machines

Generator Model Number	Number of Motors Model 1	Number of Motors Model 3	Number Current Transformers Model 1 or 3	
			No Cap.*	With Cap.*
1	1	0	0	1
3	4	2	2	12
5	18	9	6	24
7	36	18	10	40

* Cap. refers to the exciting capacity needed for power-factor correction to reduce current drain.

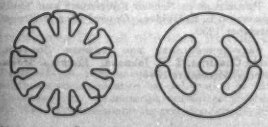


Figure 10. Possible shapes of rotor punchings for control transformer

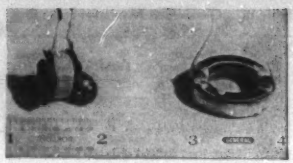


Figure 11. Miniature Selsyn using Gramme ring construction

The typical servo system of Figure 5 described previously used Selsyn generator and control transformers whose output controlled a power motor with the aid of an electronic device such as an amplifier. This is the most accurate Selsyn system and allows plenty of latitude in the choice of power control equipment. Any size of load motor can be controlled equally accurately by simple changes in the amplifier design.

Selsyn motors also may be used to control servo systems, however. If a suitable contact-making arrangement is fastened to its shaft, a Selsyn motor can control a split-series d-c motor which drives the load and at the same time repositions the stator of the Selsyn motor (ball-bearing mounted and called a control motor), until a null position is reached by the contacts. Figure 13 shows the circuit arrangement for such a servo system. Figure 14 shows a control motor disassembled. The cage in the upper part of the figure carries the stator on ball bearings, so that it may be turned by means of a gear (not shown). Alternatively, a Selsyn system similar to the foregoing might be connected to a pilot valve in a hydraulic pump and motor system thus obtaining delicate and accurate control over large forces.

All applications of Selsyn systems which use Selsyn motors as the control element suffer from the vagaries of friction in the Selsyn and the load it drives. Possible instability is thereby increased, and many manufacturing difficulties may crop up. It is best where possible to drive the shafts of Selsyns positively and employ the excellent and predictable accuracy possible with the generator–control-transformer system.

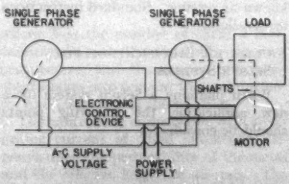


Figure 12. Selsyn servo system using single-phase Selsyns for limited-rotation application

Selsyn Errors

Errors in Selsyn systems are caused by friction or electrical discrepancies such as impedance unbalance. The reasons for the various errors and the probable magnitudes will be discussed.

Selsyn Systems Involving Selsyn Motors. These always have friction in the motor bearings and sometimes friction in the load to contend with. There is also some electrical error of the magnetic field, but usually the error due to friction is larger. Representative values of guaranteed maximum static error for pairs of like units used as indicators are given in Table III.

The insertion of another Selsyn, such as a differential, or the presence of appreciable line impedance reduces the torque that can be developed by the Selsyn motor, and therefore increases its error. For example, a Selsyn generator and motor system of model-3 series has a guaranteed static error of not more than ±0.6 degree maximum; the insertion of a differential generator of the same size increases the system static error by from 50 per cent to 75 per cent. The effect of line impedance on torque can be seen in Figure 15. Error presumably will change inversely with torque. The addition of several Selsyn motors in parallel will reduce the available torque per motor and therefore increase the error of each.

Selsyn motors have dampers to reduce unwanted oscillations, but during changing conditions or continual motion a certain amount of oscillation is likely to be present. These dynamic errors vary considerably, but it is easily possible to have errors twice or three times those for static conditions. It is important to note that this oscillation is inherent in generator–motor systems and is almost impossible to remove. Variations in torque caused by line-impedance unbalance will of course accentuate this trouble.

Selsyn-Generator–Control-Transformer Systems. These have only electrical errors which under static conditions involve inherent errors due to the design of the units and manufacturing errors due to the various tolerances between parts. When a curve was drawn of error versus angle of rotation from some reference point for a certain design, the inherent error was found to be principally a sixth harmonic of rotation, whereas the manufacturing errors tend to be second harmonics. Reduction of the second harmonic may be possible by better control of manufacture; the reduction of the

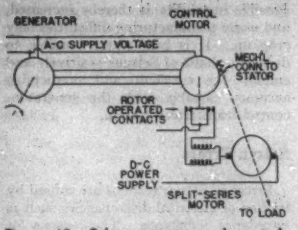


Figure 13. Selsyn-generator and control-motor contact follow-up system

sixth harmonic is possible only through a change in design.

The maximum error of a reasonably good generator–control transformer is not more than ±0.3 degree. Insertion of a differential Selsyn will increase this maximum error about 75 per cent. It will be noted that among other advantages the generator–control-transformer system has approximately one half the error of a generator–motor system. Improved design will better these figures.

One of the sources of errors in Selsyn systems is unbalance of the line impedances. It has been found necessary to keep the sections of the exciting capacity used for differential Selsyns balanced within 1 per cent. In the case of one control transformer it was found that a 1 per cent unbalance in resistance in the stator windings caused nearly a ten per-cent increase in maximum error. Balanced loads may be connected safely, but unbalanced loads change impedance and cause time-phase differences between the currents of the various circuits, resulting in an extraneous voltage or error appearing.

Each Selsyn generator–control-transformer system has an inherent limit of accuracy, as the output-voltage signal of the control transformer becomes too small for convenient use at very small angles from correspondence. By paralleling the original Selsyn system with another geared up by 16–1 to 36–1 it is possible to multiply the accuracy of any given system and obtain very much smaller system errors. The two systems can be synchronized automatically electrically, so that the low-speed system prevents the high-speed system from pulling-in on a false zero point.

One operational error in generator–control-transformers system is worthy of note. Rotation of the system produces generated voltages in the control-transformer output in addition to those induced by transformer action. The magnitude of this effect is dependent on the Selsyn impedances and usually may be

Table III. Guaranteed Maximum Static Error

Model Number	Maximum Static Error, Degrees	Model Number	Maximum Static Error, Degrees
1	1.5	2	1
3	0.6	4	1
		6	1

Figure 14. Selsyn generator with ball-bearing-mounted stator showing stator support and brush rigging

compensated for at a given speed only. For 60-cycle units the control transformer will lag the generator by 0.5 degree to one degree when rotating at 200 rpm.

Selsyn Application Suggestions

Selsyns are high-grade accurate instruments and should be treated as such. Ordinary tests in the field can check only the continuity of the wiring and do not give any indication of the accuracy of a unit. Selsyns are built to withstand all reasonable conditions of operation, but careful handling is a requisite during installation. Manufacturer's suggestions on mounting should be followed if the best use is to be made of them.

Zeroing

In order to provide a reference position from which to measure rotation, for each Selsyn type there has been arbitrarily designated a combination of stator and rotor voltages and corresponding relative positions known as zero positions. The procedure of locating these positions is known as zeroing. Standard instructions are available.

Application Specifications for Selsyn Systems

When planning a Selsyn system for a new application the following points should be considered.

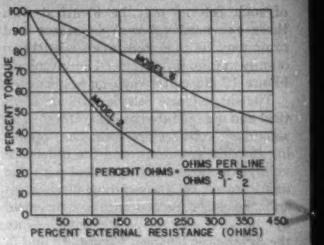


Figure 15. Variation of motor torque with line impedance for models 2 and 6

1. Is a generator-motor or a generator–control-transformer system indicated?

2. Check supply voltage and frequency. Determine allowable drain in watts and amperes and regulation of supply.

3. What are requirements of load in torque, speed of rotation, duty cycle, accuracy? Will any tendency of a generator-motor system to oscillate be objectionable?

4. Determine limiting conditions at application location: temperature, humidity, dirt, vibration, shock, and so forth.

5. Does the generator have a stiff driving mechanism, or is the friction of bearings and brush rigging important? If a generator-motor system is used, can the driving mechanism handle the friction of both machines as well as the load?

6. Are the line impedances balanced, including any exciting capacities?

7. Are the method of mounting, the gearing, and so forth accurate enough to make the best use of the Selsyn system?

An understanding of the general principles of Selsyn system operation is the best guide to satisfactory applications; with it the possibilities for greatly increased use of Selsyn-controlled systems will come into use rapidly in industry.

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Optimum Air Gap for Various Magnetic Materials in Cores of Coils Subject to Superposed Direct Current

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Synopsis: A method is developed for calculating optimum air gap and core size for choke coils whose windings must carry direct current in addition to alternating current. It is employed with data on typical magnetic materials to give curves from which design dimensions can be obtained readily to fulfill specified requirements for inductance, resistance, and d-c burden.

THE PROBLEM of proper proportioning of air-gap and metallic-path length of the magnetic core of choke coils and transformers frequently arises in the design of coils whose windings must carry direct current along with the desired alternating current. This problem has been approached in the past along lines laid down by Hanna.[1] This involved calculations based on known characteristics of the magnetic materials and taking into account the effects of air gaps of various lengths inserted in the magnetic circuit. Taking an estimatedly correct core volume, V, the optimum value of applied field then was computed, from which the number of turns in the coil was obtained. The resulting coil resistance then was calculated to see if it was satisfactory. If not, a new core volume was assumed, and the calculations were repeated until the desired winding resistance was attained.

It has seemed that a more direct approach to optimum dimensions could be devised, which would give an immediate answer as to the suitability of any given core material for a specified inductance, resistance, and d-c burden. An analysis of the problem has been made, and curves have been plotted for several important magnetic materials from which design dimensions can be readily obtained.

General Problem: L, R, and I Specified

The general method is based on the known fact that prerequisites of inductance L, resistance R, and d-c burden I, can be met by proper expansion or contraction of the size of a core, leaving the ratios of dimensions fixed. Thus, for example, all dimensions can be expressed as fixed multiples of the metallic core length. The essential equations then can be set up and solved for minimum core length. This gives relationships between the (μ, B) curve, (μ_r, B) curve, and the specified L, R, and I of the coil, which must be met for the optimum conditions. The necessary metallic path length, air-gap percentage, and number of turns in the coil follow directly.

Considerable study has been given by others to determine the ratios of dimensions in various types of coils to apportion space properly to windings and magnetic materials. The present analysis assumes that technically or commercially approved dimension ratios are known for whatever coil and core configuration may be considered and confines itself to determination of core and air-gap relationships. If the metallic-path length is l, the average length of a turn of wire in the winding will be ul, the area available for copper winding will be vl^2, and the cross-sectional area of the magnetic core will be wl^2, where u, v, and w are known constants. The length of the air gap is similarly αl, where the factor α is to be adjusted to make l as small as possible. Air gaps will be initially assumed so short as to avoid fringing, so that the flux density in the air is as great as that in the metal. Necessary adjustments to take account of fringing with longer air gaps will be described.

With these assumptions the specified resistance R, inductance L, and d-c burden I enter into the equations as follows.

The resistance of the copper winding will be proportional to the total length of wire ($N \times$ average turn length, ul) and inversely proportional to the cross-sectional area per turn, vl^2/N, or

$$R = \frac{\rho N u l}{v l^2/N} = \frac{u \rho N^2}{v l} \text{ ohm} \qquad (1)$$

where N is the number of turns, l is in centimeters, ρ is the resistivity in ohm-centimeters, and the copper area constant v takes into account the packing factor and insulation of the winding.

The inductance, as measured with alternating current of small amplitude, depends upon the permeability of the metal and the relative length of air gap. The permeability to be used is the a-c permeability at the value of superposed field set up by the direct current in the winding. For simplicity only the reversible permeability μ_r will be considered. The results for values of alternating current differing from zero will approximate quite closely those obtained for zero current, namely, μ_r. This follows from the fact that the a-c permeability changes less with changing current in the presence of superposed field than without. The inductance is derived from the basic equation

$$L = \frac{N\Phi_m}{i_m} \times 10^{-8} \text{ henry}$$

where Φ_m is the peak flux in maxwells corresponding to the a-c peak i_m, in amperes. The flux can be written as the ratio of magnetomotive force, $0.4\pi N i_m$, to the reluctance, $l/wl^2\mu_r + \alpha l/wl^2$, whence

$$L = \frac{4\pi N^2 w l}{l + \mu_r + \alpha} \times 10^{-9} = 4\pi N^2 \mu_e w l \times 10^{-9} \qquad (2)$$

where μ_e is the effective permeability, that is, the permeability of a uniform core material occupying the same space as the

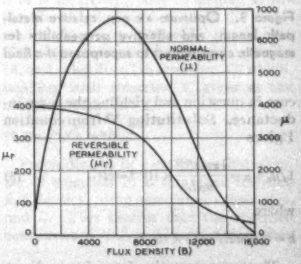

Figure 1. Normal and reversible permeability of four-per-cent silicon iron

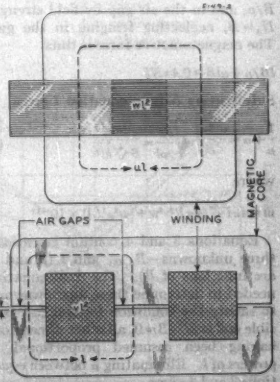

Figure 2. Typical shell-type core with relative dimensions indicated

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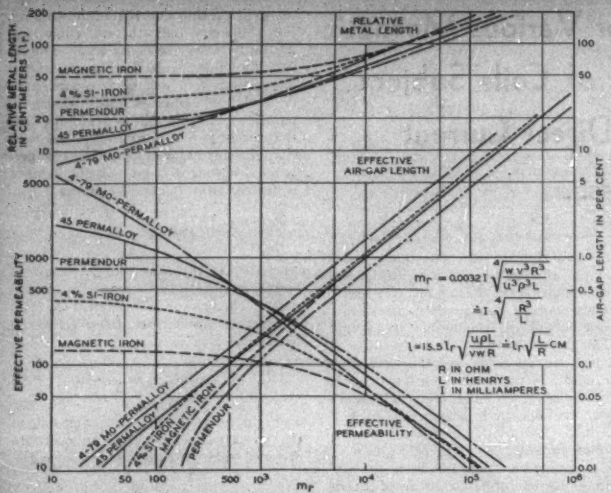


Figure 3. Optimum air gap, relative metal-path length, and effective permeability for magnetic cores subject to superposed d-c field

core in question and yielding the same inductance. Substituting N^2 from equation 1 gives

$$1/\mu_r+\alpha=\frac{4\pi vwRI^2}{u\rho L}\times 10^{-9}=kI^2 \qquad (3)$$

where

$$k=(4\pi vwR/u\rho L)\times 10^{-9}$$

The magnetomotive force due to direct current in the winding is distributed between the magnetic core and the air gap so as to maintain the steady flux density B in the core by means of field strength $H=B/\mu$, and in the air gap by field strength $H_a=B$, neglecting fringing in the gap. The magnetomotive force is thus

$$lB/\mu+\alpha lB=0.4\pi NI$$

Substituting N from equation 1 gives

$$\frac{1}{\mu}+\alpha=\frac{0.4\pi I}{B}\sqrt{\frac{Rv}{u\rho l}}=\frac{m}{B\sqrt[4]{kI^2}} \qquad (4)$$

where

$$m=4\pi I\sqrt[4]{(4\pi R^2v^2w\div[u^2\rho^2L])\times 10^{-12}}$$

Equations 3 and 4 contain essentially three unknowns—B, α, and l (μ and μ_r are functions of B). The final equation needed to determine these unknowns and to satisfy the condition for smallest possible coil is $dl/dB=0$, all other dimensions having been assumed proportional to powers of l. Eliminating α between equations 3 and 4 gives

$$B\sqrt{kI^2}(1/\mu-1/\mu_r+kI^2)=m \qquad (5)$$

Differentiating with respect to B and setting $dl/dB=0$ gives

$$kI^2=\frac{1}{\mu_r}-\frac{1}{\mu}+B\left[\frac{1}{\mu^2}\frac{d\mu}{dB}-\frac{1}{\mu_r^2}\frac{d\mu_r}{dB}\right]=\frac{1}{\mu_r}-\frac{1}{\mu}+B\Delta \qquad (6)$$

where

$$\Delta=\left[\frac{1}{\mu^2}\frac{d\mu}{dB}-\frac{1}{\mu_r^2}\frac{d\mu_r}{dB}\right]$$

Substituting this value of kI^2 back into equation 5 gives

$$B^2\Delta\sqrt[4]{B\Delta+1/\mu_r-1/\mu}=m \qquad (7)$$

This equation gives the optimum value of B for the desired value of m, but it also implies selection of corresponding values of μ, μ_r, $d\mu/dB$, and $d\mu_r/dB$, to satisfy the equation. These functions must be determined from (μ, B) and (μ_r, B) curves such as shown in Figure 1 for four per cent silicon iron. On account of the involved nature of the data, equation 7 is handled most readily in reverse direction, by inserting known values of B, μ, μ_r, and so forth, from the magnetic data and solving for the constant m. Such calculations from the curves of Figure 1 are given in Table I.

The value of the air-gap ratio is obtained from equations 3 and 6 as

$$\alpha=B\Delta-1/\mu \qquad (8)$$

The metallic-path length from equation 6 is

$$l=\sqrt{(B\Delta+1/\mu_r-1/\mu)/k} \qquad (9)$$

A function which reveals the influence of the air gap is the effective permeability, μ_e. Thus, from equations 2 and 8

$$\mu_e=\frac{1}{1/\mu_r+\alpha}=\frac{1}{B\Delta+1/\mu_r-1/\mu} \qquad (10)$$

The necessary number of turns in the winding follows from equations 1 and 9.

It is now feasible to plot pertinent data of air-gap and metal length for any desired magnetic material against values of m. From such curves essential dimensions of any coil can be read off immediately when m has been computed. For practical purposes it is convenient to use values for m corresponding to typically proportioned cores. The parameters in the foregoing equations are

$$m=4\pi I\times 10^{-4}\sqrt[4]{4\pi R^2v^2w/(10u^2\rho^2L)} \text{ and}$$

$$k=4\pi vwR\times 10^{-9}\div(u\rho L)$$

where I is in milliamperes, R in ohms, ρ in ohm-centimeters, L in henrys, and l is in centimeters. The constants u, v, and w will have various values, depending on the shape of the core, whether annular, shell type, or otherwise. Under the assumption that shell-type cores as illustrated in Figure 2 are most common for use with air gaps, typical cores have been measured for values of the dimension ratios. Thus $u=1.8$, $v=0.02$, and $w=0.04$, approximately. Inserting these values in the above equations gives

$$\left.\begin{aligned} m&=4.17\times 10^{-3}IR\div\sqrt[4]{RL} \\ \text{and}\quad k&=3\times 10^{-3}R/L \end{aligned}\right\} \qquad (11)$$

For cores having such typical dimension ratios, it is convenient to express results in terms of

$$m_r=IR\div\sqrt[4]{RL}=m\div(4.17\times 10^{-3})$$

Table I. Data and Computations for Four-Per-Cent Silicon Iron

B(gauss)	2,000	4,000	6,000	8,000	10,000	12,000	15,000
μ	4,520	6,150	6,740	5,950	4,550	2,600	430
$d\mu/dB$	1.03	0.45	0	−0.56	−0.85	−1.00	−0.42
μ_r	386	369	343	294	188	95	20
$d\mu_r/dB$	−0.007	−0.010	−0.017	−0.034	−0.068	−0.031	−0.008
$\Delta\times 10^3$	98	85	144	377	1,889	3,292	17,720
$kI^2\times 10^3$	2.56	2.89	3.63	6.25	24.0	49.5	313.5
m	0.0882	0.315	1.27	6.77	74.2	2,230	29,900
m_r	21.15	75.6	305	1,625	17,800	535,000	7,170,000
α (per cent)	0.218	0.018	0.072	0.285	1.87	3.90	26.3
l_r	29.2	31.0	34.7	45.6	89.5	128.5	
μ_e	386	346	276	160	41.6	20.2	3.3
LI^2/V	0.478	5.09	50.4	740	11,780	3,120,000	
$(N/l)\sqrt{V/L}$	451	479	536	704	1,383	1,985	
$NI/1\times 10^{-3}$	0.312	1.082	4.13	19.18	150.0	3,760	

Values of m_r have been computed as given in Table I for four per cent silicon iron. They have been used as abscissas in Figure 3, for plotting optimum air gap and effective permeability of four per cent silicon iron. Computations similar to those in Table I based on published magnetic data[3] have been made for magnetic iron, Permendur, 45 Permalloy, and 4–79 molybdenum-Permalloy, and the results plotted in Figure 3.

An additional family of curves is shown in Figure 3, labeled relative metal length, l_r. The necessary metal length from equation 9 involves k, for which an expression is given in equations 11 for typical core dimension ratios. If the ratio R/L is taken as unity, the typical value of k is 3×10^{-4}. With this value "relative metal-path lengths" have been computed from equation 9. The actual core length in any given case then would be $l_r\sqrt{L/R}$.

If other values of u, v, and w are to be used than the assumed typical values the curves of Figure 3 apply if the abscissas are calculated from the equation

$$m_r=(4/4.17)\pi I\times10^{-1}\sqrt[4]{4\pi R^3v^3w}/(10u^2\rho^2L) \tag{12}$$

Similarly the correct metal length l will be obtained from equation 9 in terms of the relative length l_r given in the curves by the equation

$$l=l_r\sqrt{3{,}000u\mu L/4\pi wR} \tag{13}$$

Special Case I. L, I, and l (or V) Specified

The problem thus far has assumed complete freedom in the choice of dimensions. Frequently, however, the problem may begin with a certain size of core and inquire after the optimum air-gap length to provide a specified inductance in the presence of a given amount of direct current. In this case it will be necessary to adjust the coil resistance along with the air-gap length to satisfy the optimum conditions. The problem becomes that of ascertaining the values of l_r and m which correspond to the optimum conditions as defined by the above equations and which yield the specified inductance and metallic-path length for the specified current.

The metallic-path length l is known in this case, but l_r and R in equation 13 are not known. Substituting the value of R from equation 13 in equation 12 gives

$$\frac{26.6m_r^3}{l_r^3}=\frac{LI^2}{wl^2}=\frac{LI^2}{V} \tag{14}$$

where V is the volume of the core. This resembles the fundamental equation derived by Hanna,[1] but it has the advantage that m_r and l_r can be computed for any given flux density and material by the methods here described. If the first member of equation 14 is computed using associated values of m_r and l_r which already satisfy the optimum conditions, it yields the necessary parameter to insure that the corresponding l_r and α are optimum under the specified conditions of L, I, and l.

With optimum values of l_r and α, the required number of turns in the winding from equations 1 and 13 becomes

$$N=l_r\sqrt{\frac{3{,}000L}{4\pi lw}}=ll_r\sqrt{\frac{3{,}000L}{4\pi V}} \tag{15}$$

The resistance in the winding then follows from equation 1.

The data used for Figure 3 have been analyzed further to find the values of LI^2/V which correspond to the optimum values of m_r, l_r, and α. The results have been plotted in Figure 4, showing values of

$$l_r\sqrt{3{,}000/4\pi}=(N/l)\sqrt{V/L}$$

and α against LI^2/V.

Case II. L, N, (or R), and l (or V) Specified

If inductance is specified, and it is desired to know the percentage air gap required to permit the use of the largest possible direct current in the winding of a coil which is already constructed, the curves in Figure 4 can again be used. All of the factors required to compute $N+l\sqrt{V/L}$ now are specified. It remains only to locate the indicated point on the $N+l\sqrt{V/L}$ curve for the material of which the core is constructed, and read the corresponding value of LI^2/V. From the latter value can be calculated the maximum current which can be employed without understepping the specified inductance.

The necessary air-gap length can be read off directly from Figure 4.

Case III. N (or R), I, and l (or V) Specified

If the d-c burden is specified, and the coil is already constructed (that is, l and N or R are fixed) it may be desired to adjust the air-gap length to yield the maximum inductance. Proceeding as in case I, the inductance is solved for in equation 13, and substituted in equation 12, which, together with equation 1, gives as the necessary relation

$$79.6m_r/\sqrt{l_r}=NI/l \tag{16}$$

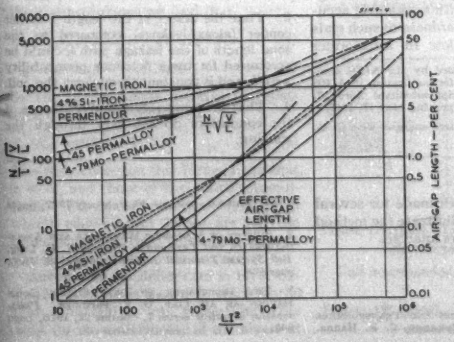
Proceeding as in case I, the first member of equation 16 is computed for each flux density, using associated values of m_r and l_r. This insures that the specified conditions of N, I, and l are satisfied when

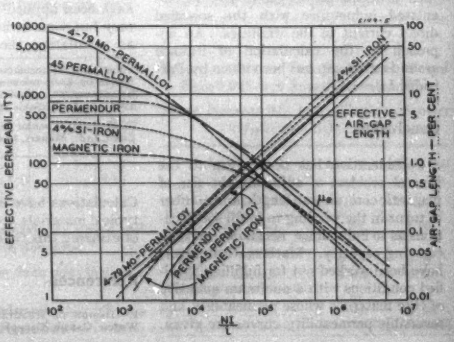
Figure 4. Optimum air gap and number of turns for a coil having specified inductance, core size, and d-c burden

L in henrys
I in centimeters
l in milliamperes

Figure 5. Optimum air gap and permeability for a coil having specified inductance, core size, and d-c burden

L in henrys
I in centimeters
l in milliamperes





the optimum conditions of l_t and α are employed. Curves in Figure 5 give the effective permeability and air gap plotted against NI/l. The inductance attained with the values of μ_e and α so chosen will be the maximum possible. The inductance in henrys is computed from equation 2.

Case IV. N (or R), L, and l (or V) Specified

If the inductance is specified and the coil is already constructed, the curves of Figure 5 can be read backwards to find the allowable direct current and the necessary air gap.

Case V. N (or R), l (or V), and α Specified

If a finished coil is at hand, the question may arise as to the direct current which should be used to employ the core and coil most efficiently. Curves on Figure 5 may be used in this case to locate the value of NI/l which corresponds to the specified value of α. With this value of NI/l, optimum current is computed. Similarly the corresponding effective permeability is read from the curves, from which the optimum inductance is found.

The Air Gap

The foregoing analysis has been concerned with determining the optimum air-gap length to satisfy certain conditions. When the practical question arises as to the number of millimeters spacing to insert, still further analysis is required, on account of magnetic fringing at the gap. In general a longer physical gap must be inserted into the magnetic circuit than indicated by the optimum percentage. The correction is less for very short gap lengths, or if the total amount of gap is divided into two or more short sections with interspersed core material. The correct gap length can be found empirically by building the coil as designed and then adjusting the air gap to give the calculated inductance with the specified direct current in the windings. An approach to the calculation of leakage around an air gap has been given by Partridge.[3]

Conclusion

Consideration has been given to the general problem of adjusting the size of magnetic core, air-gap length, and number of turns in the winding to fulfill specifications as to inductance, resistance, and d-c carrying capacity. Mathematical means have been worked out for fulfilling specified conditions with a minimum quantity of core materials whose permeability and reversible permeability curves are given. Calculations have been made for several typical materials, to illustrate the method of utilizing this type of analysis.

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Eddy-Current Resistance of Multilayer Coils

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Synopsis: Most of the earlier studies of eddy-current resistance have been made by those interested primarily in the effect of compromise transpositions on the losses of rotating equipment. Their results have included formulas for the eddy-current resistance for perfect transpositions, but these have gotten into handbooks in difficult form or have been ignored entirely. Such formulas are presented here in more usable form, with more information on their limitations, and further formulas are derived for minimum losses for a number of different cases. Included is a set of curves showing eddy-current resistance as a function of the number of layers and conductor thickness. Formulas also are included that take into account the differing lengths of conductor in successive layers and that approximate the end losses in a spiral coil on account of radial flux.

THE CUSTOMARY approach to the problem of eddy-current-loss calculations for multilayer coils has been to assume a coil side surrounded on three sides by a medium of infinite permeability and no loss and the use of rectangular conductors. There has been one exception to this that is discussed later.

The principal aim of most of these investigations has been to arrive at a loss factor that might be applied to the d-c resistance of slot windings of various types to find the effective or a-c resistance. This has included evaluating the loss factor for the individual layers, which is all that needs to be applied if the layers are in series or if a perfect transposition system is used, and a different loss factor that includes the circulating current caused by compromise transpositions in certain practical windings.

Formulas so derived for slot windings have been applied with reasonable accuracy but some awkwardness to such ends as calculating the loss in transformer coils. It is the purpose of the present work to derive a formula that can be modified readily to account for the difference in layer lengths, and that will lead to simple and general approximate formulas that can be used for a very rapid survey of design possibilities in many cases.

A paper by Butterworth[2] considers an inductance without the usual partial iron circuit and wound with round conductors. It is shown that the ratio of reactance to resistance is a maximum for a coil so proportioned that the ratio of diameter to length is from 2.5 for low frequencies to 3.2 for high frequencies, the distinction between low and high frequencies being made according to the degree to which skin effect is evident in an isolated conductor. At high frequencies the reactance-to-resistance ratio is improved by a spaced winding. Formulas are derived for losses in such coils and shown to correspond to measured results. It also is shown that for the coils in question the losses are almost entirely due to the radial component of flux rather than the axial component. As these results are limited in their application to single-circuit systems (also end-to-end coupling) of rather limited proportions, they are not considered further here.

Returning to the more usual analysis of eddy-current problems, it has been customary to assume further that:

1. The conductors could be represented by rectangular bars of the type shown in Figure 1A, so disposed that two of their flat surfaces are parallel to the general direction of the leakage flux.

2. That component of leakage flux parallel to the other two flat surfaces could be neglected.

3. That the defect in the length l of net copper (along leakage) compared to the total length of the leakage path l_t could be accounted for by a fictitious permeability $\mu = l/l_t$ and is constant throughout the coil.

4. That the temperature and resistance of the conductors do not vary through the winding.

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Coil Loss and Effective Resistance

In the derivation outlined in the appendix additional assumptions have been made to the effect that the eddy-current losses in question are due only to the current in the coil being examined and that this current is in phase through all of the layers comprising the coil. Appropriate modifications for other cases are reasonably obvious and have been given by Lyon, among others.

It is shown in equation 33 that the loss in the nth layer is, in watts

$$wA = B_\Delta^2 C_1 A\,[(2n^2-2n+1)F_1+F_2] \qquad (1)$$

n which

B_Δ = increment in leakage-flux density through layer in lines per square inch

$C_1 = 1.935 m_\rho 10^{-8}/n^2$

A = area in square inches of one surface of conductor parallel to leakage flux

$x = 1.01 r_1 \sqrt{\mu f/\rho}$ (r_1 is in inches, see Figure 1B)

f = frequency in cycles per second

$F_1 = x^3/48 - x^5/18{,}660$

$F_2 = 2/x - 14x^3/1{,}440$

$\mu = l/l_1$

$m = 0.505\sqrt{\mu f/\rho}$

ρ = microhms per centimeter cube

w = watts loss per square inch of A

Precise definitions of F_1 and F_2 are given in the appendix.

From this result it follows that the sum of these losses from $n = 1$ to $n = N$ is, in watts

$$B_N^2 C_1 A\,[(2N^3+1)F_1/3+F_2]/N \qquad (2)$$

where B_N is the highest flux density associated with the Nth layer under the original assumptions. For comparison it is shown in equation 41 that the loss neglecting eddy current is $2B_N^2 C_1 A/Nx$. Therefore it follows that

$$R_{ac}/R_{dc} = (x/2)\,[(2N^3+1)F_1/3+F_2] \qquad (3)$$

When $x < 2$ the error involved in approximating F_1 and F_2 by writing their series to the first terms in x with positive exponents amounts to +4.5 per cent and −0.4 per cent, respectively. Making these substitutions we find that

$$W = B_N^2 C_1 A\,[x^3(5N^3-1)/360+2/x]/N \qquad (4)$$

$$R_{ac}/R_{dc} = x^4(5N^3-1)/720+1 \qquad (5)$$

So the proportionate increase in resistance due to eddy current is

$$R_e/R_{dc} = x^4(5N^3-1)/720 \qquad (6)$$

The restrictions on this formula are that $x < 2$, and those of the stated assumptions. For most practical designs in which eddy-current losses are on the order of ten per cent, this approximation gives results of slide-rule accuracy.

Accounting for differences in layer circumferences, it is shown in equation 38 that if a_0 and a_1 are, respectively, the radii (or circumferences) of the layers at zero and maximum leakage-flux densities, the loss for the coil is

$$W = (B_N^2 C_1 A/N)\left\{F_1\left[\frac{2N^3+1}{3} - \frac{3N^3+N+1}{6}\,\frac{a_0-a_1}{a_0}\right] + F_2\,\frac{(a_0+a_1)}{2a_0}\right\} \qquad (7)$$

From this and from equation 41 it follows that, for $x < 2$,

$$R_e/R_{dc} \approx \frac{x^4}{720}\left\{5N^3-1 - \frac{15N^3+5N+5}{4}\,\frac{a_0-a_1}{a_0}\right\}\frac{2a_0}{a_0+a_1} \qquad (8)$$

Derivations for Minimum Loss

The minimum practicable loss in an a-c coil is usually desirable, and in order to investigate the relation between parameters for this condition it will be convenient to use equation 4. This may be treated as a variable in either N or x and the condition for minimum loss determined by setting the appropriate differential equal to zero.

This shows that when N is variable the losses are a minimum when $N \approx 12/x^3$, and that when x is variable the condition for minimum loss is that $x = \sqrt[4]{240/(5N^3-1)}$.

Substituting these relations successively in equation 5, we find that if N is variable minimum loss corresponds to $R_e/R_{dc} = 1$, and that if x is the variable minimum loss corresponds to $R_e/R_{dc} = 0.33$. This may seem a little surprising at first glance, but the first relation simply represents a less efficient use of conductor. It is necessary that the relationships be different in order that they be valid. For any particular frequency either relation can be shown to be a condition for a maximum in the ratio of reactance to resistance.

These two cases are of more academic than practical interest at standard frequencies except in the case of air-core reactors, since they assume that economy is unimportant as applied to conducting material and space. At radio frequencies, and even at lower frequencies, economy of conducting material and space is not important as very little of either can be used from considerations of energy economy.

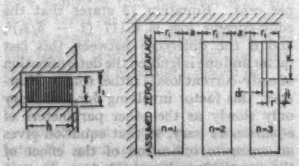

Figure 1A (left). Geometrically simple coil side assumed in derivation

Coil is surrounded on three sides by iron

Figure 1B (right). Enlarged view of one corner of Figure 1A

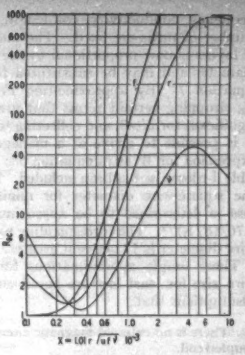

Figure 2. Effective resistance of 100-layer coil plotted against x

Three cases are shown to illustrate the effect of varying f, r_1, and γ independently

Equation 4 can be rewritten as a function of ρ by writing out the various terms included in C_1 and x. Then by setting the differential with respect to ρ equal to zero it can be shown that the losses are a minimum when ρ is such that $N \approx 12/x^3$. This is the same as the condition for minimum losses with N variable.

It can be shown that where both direct and alternating currents are present in a coil the total loss is

$$W = (2B_N^2 C_1 A/N)\,\{x^3(5N^3-1)/720+k_b/x\} \qquad (9)$$

where $k_b = 1 + 2I_{dc}/I_{ac}$ in which the ratio is taken for the peak value of the a-c wave, and B_N refers only to the alternating component of flux. From this it can be shown that if x is taken as the variable the losses are a minimum when

$$x = \sqrt[4]{240k_b/(5N^3-1)} \qquad (10)$$

A somewhat more practical case is for square or round wire and for which the

Table I. Data on Two Small Coils Wound From 0.022-Inch Round Enameled Wire

Inside Diameter 13/16 Inch, Outside Diameter 1 1/16 Inches, Eight Layers

	Long Coil	Short Coil
Turns	686	332
Length, inches	2	1
D-c resistance, ohms	3.88	1.93
Axial space factor for equivalent rectangular wire	0.83	0.83
Nagaoka's constant	0.828	0.709
Millihenrys at 1,000 cycles per second	3.97	1.93
μ	0.687	0.583
$x/f^{1/4}$	0.01273	0.01173

frequency, conductivity, coil length, and number of turns are fixed. The number of layers is now proportional to the wire diameter and may be substituted for in equation 7. By approximating F_1 and F_2, dropping certain terms that are not significant for $N>3$, and collecting terms, it is possible to arrive at a manageable expression for W as in equatiou 53; possible d-c loss also has been included. Then the square-wire diameter for minimum loss is determined to be approximately $2.76/(lf/1_2)^{1/2}$. The corresponding round-wire diameter is 12 per cent greater.

These simple approximations for the wire size for least loss are based on the assumptions that:

1. There is no external magnetic circuit or coupled coil.
2. There is no unidirectional component of current.
3. Coil length ≈ effective coil diameter and $a_0 \approx 2a_1$.

If these conditions are not all fulfilled a more exact solution for the wire diameter for minimum loss from equation 56 should be used. Any one of the foregoing items readily can influence the wire diameter by one gauge number (12 per cent).

Figure 7 shows the relation between frequency, turns per inch of coil length, and round-wire diameter for minimum loss based on the approximations in equation 57 outlined in the foregoing.

For comparison with the minimum-loss, cases in which N, X, or ρ are independent variables, the value of x from equation 55 can be substituted in equation 6, assuming that $k_3=1$ and that $a_0=a_1$ so that $k_4=0.5$. Then $R_s/R_{dc}=0.5$.

In this last case for least loss it has been assumed tacitly that in the absence of an external magnetic circuit (see Figure 1) the radial field could be ignored. Some justification is given for this later.

A situation that is more frequently of practical importance is the case in which dimension h of Figure 1A, that is, the radial thickness of the coil, is fixed, and the insulation required between laminations is of fixed thickness. Ordinarily extra insulation will be required between conductors, and still more extra insulation between coil sides, but these extras may be lumped together as a constant before determining h. In this case N is a function of x, or $N = 2mh/(x + 2m\delta)$; this value for N can be substituted in equation 7, and, after approximations that are reasonably good for $N > 3$, the value of r_1 for minimum loss can be found from

$$r_1q/\delta = \sqrt[3]{\frac{9}{2\delta^2h^2m^4}\,\frac{2k_4}{3k_4-1}} \qquad (11)$$

where $k_4 = (a_0 + a_1)/2a_0$, and $q = \{(1 + 3\delta/2r_1)/(1 + \delta/r_1)^3\}^{1/3}$; r_1/δ may be plotted as a function of r_1q/δ and then this may be used as a step in determining r_1. As an approximation when $r_1/\delta > 1$, and to slide-rule accuracy when $r_1/\delta > 3$,

$$r_1 = \delta\left(0.17+\sqrt[3]{\frac{9}{2\delta^2h^2m^4}\,\frac{2k_4}{3k_4-1}}\right) \qquad (12)$$

An instructive approximation can be made from equation 12 when $r_1/\delta > 4$, and if the influence of k_4 is neglected, the value of r_1 for minimum losses becomes

$$r_1 \approx \sqrt[3]{\frac{9\delta}{2h^2m^4}} \qquad (13)$$

This can be substituted back into equation 6 along with the definition of N in terms of r_1, and the eddy-current loss for that value of r_1 that makes the total loss the least can be determined as

$$R_s/R_{dc} \approx (1/16)(m^4h^2\delta^2)^{1/3}(1-\delta/r_1)^3 \qquad (14)$$

To take a numerical example assume that at 60 cycles

$m=2$
$h=6$ inches
$\delta=0.01$ inch

Then, for minimum-loss equation 12 determines r_1 to be 0.0444 inch and N to be 110 layers, and as $x = 0.1776$ equation 6

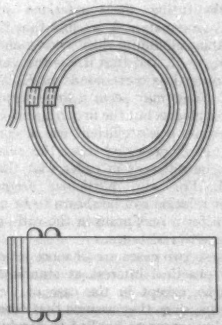

Figure 3. Three-turn spiral with three parallels showing simple method of transposing

evaluates the eddy-current loss at 8.35 per cent. Equation 14 states that the eddy-current loss is $0.117\ (1 - \delta/r_1)^3$, and if the difference between this last factor and one is ignored the determination of eddy-current loss is rather rough. However, this factor involving δ/r_1 will vary only slowly as the other parameters of equation 14 vary, so that equation gives an accurate indication of the effect of these variables when $r_1/\delta>4$.

Effect of Radial Component of Field

The work up to this point has assumed that the winding is surrounded on three sides by a medium of infinite permeability and no loss so that the loss for rectangular conductors could be determined quite precisely under the assumption of no radial component of field. If the external circuit be removed the situation becomes quite different, whether the conductors are round or rectangular.

By measurement on an eight-layer coil (described later) in which the length was about equal to the diameter, the field strength along the axis of the coil varied about 50 per cent from the center to the ends, and the radial component at the ends was not much less than the axial component at the ends. It would seem that in such a case, as far as losses are concerned, the presence of the radial field would just about make up for the deficit in the axial field. Experiment shows this to be the case, and, when the ratio of coil-length to diameter is greater than one, eddy-current losses can be approximated reasonably by using equation 6 with r_1 determined as the diameter of a square wire having the same cross section as the actual round wire. In this case μ should be determined as the space factor of the assumed square wire in the axial direction multiplied by a factor giving the ratio between the actual inductance and the inductance calculated from the long-coil formula. Such a factor can be approximated from Nagaoka's constant by using for coil diameter the actual diameter plus two thirds of the radial depth.

When $l_2/D>0.3$, Nagaoka's constant can be approximated to within two per cent by $1.02-1/(1+2l_2/D)$ in which l_2 is the axial length of the coil and D is the effective diameter of the coil.

It should be pointed out that, if the radial thickness of a winding is less than about one quarter of the effective coil diameter and also less than one quarter of the coil length, the eddy-current loss may be mainly the result of the radial component of field, and the formulas derived here cannot be used correctly.

These formulas are intended for concentrically coupled coils having equal and opposed ampere turns, and for other coils in which the coil geometry indicates that most of the eddy-current losses are due to the axial field. For concentrically coupled coils, the effective diameter can be taken as the radial distance between coils plus one third of the sum of their radial thicknesses.

In the case of coils wound with rectangular conductor with the flat of the conductor parallel to the principal magnetic field, the situation is not so clear, as a given radial field can produce much higher losses on account of having a wider conductor to work on.

It is quite apparent that the losses will be reduced by any steps that will reduce the radial component of field, and this dictates the use of coils that are long as compared to their diameter, and what

amounts to the same thing, the close coupling of load coils either inside or outside the coil being studied.

As a one-turn-per-layer coil has no radial field except at the ends when energized by alternating current the use of such a coil may represent a step in the right direction when a considerable conductor area per turn is required. From a practical point of view such a coil has the additional recommendation that voltage stresses from steep-wave-front transients are distributed rather equally between turns, because the turn-to-turn capacity is large and quite uniform, and all except the first and last turns are quite well shielded from ground. Figure 3 is an illustration of such a coil, and it also shows a transposition system that can be used when the number of turns must be less than the number of layers.

It should be noted that if other conditions are appropriate the end losses for a one-turn-per-layer coil will be the same as for a two-turn-per-layer coil formed by assembling two spirals each half as long and suitably connecting them in series. It would seem that spiral coils would represent the most efficient construction possible since they have radial field losses only at the ends; a possible exception would be those cases in which conductors can be used for which the x measurement, determined for the radial field, can be less than one or two. This follows as otherwise the losses at the ends will be about the same in any case, and the spiral construction eliminates radial field losses through the rest of the coil.

In practical constructions the conductor width of such spirals will be limited to perhaps five inches or less by considerations of heat transfer, but a number of such spirals can be assembled end to end and connected in parallel to make up any desired conductor width, with spaces between the spirals for coolant circulation.

The end losses of such a spiral coil can be approximated from equation 1 for both ends as

$$\frac{R_a}{R_{dc}} \approx \left(\frac{B_a}{B_N}\right)^2 \frac{\mu^{2/3}}{(\mu')^{1/3}} \frac{2\pi a_0 |a_0 - a_1|}{A} Nx \qquad (15)$$

in which B_a is the radial component of field strength and μ' is the radial space factor. This is not a particularly satisfactory approximation as it assumes the radial field to be constant over the end of the coil, but it at least will indicate the magnitude of the end loss to be expected.

Experimental Measurements

Round-Wire Coils

In order to test the application of formulas derived for rectangular conductors and a partial magnetic circuit to coils from round wire and surrounded by air, two small coils were wound from 0.022-inch round enameled wire, each coil having an inside diameter of 0.81 inch, an outside diameter of 1.19 inches, and eight layers. Other information is given in Table I.

The effective resistance was measured by providing a mica decade capacitor for parallel resonance and driving from the 5,000-ohm tap of an oscillator through a 33,000-ohm decoupling resistance that was noninductive. The voltage across the parallel-resonant circuit was measured by a vacuum-tube voltmeter, and then a decade resistance was substituted for the parallel circuit and so adjusted that the voltage across the resistance was the same as that which had appeared across the parallel circuit. If the capacitor loss is charged to the inductance the effective series resistance of the inductance is given by the formula: inductance ÷ (capacitance times substitution resistance).

This method is not precise but for frequencies such that $x < 2$ the change in inductance with frequency will be very small and the method is reasonably satisfactory. The reactance–resistance ratio of the coils used was roughly from 10 to 30 for frequencies from 2,500 cycles to 20,000 cycles. At the upper limit of frequency the method begins to introduce appreciable inaccuracies on account of the inductance in the resistance decade, but a check by using a carbonized resistance indicated that the error was only two or three per cent.

The results are shown in Figure 6 as two sets of points plotted and the theoretical curve of equation 8 drawn in.

Table II. Observations on 60-Turn Spiral Coil of Electrolytic-Copper Ribbon

One Inch Wide by 0.0035 Inch Thick

a_0, inches radius	0.97
a_1, inches radius	0.437
D-c resistance, ohms	0.0715
Effective ribbon thickness, inches	0.0025
μ	0.642
μ'	0.281
$m/f^{1/2}$	0.3075
Millihenrys at 10,380 cycles per second	0.0706

Table III

x	0.157	0.174	0.206	0.226
R_a/R_{dc}	2.33	2.95	3.43	3.87
R_a/R_{dc} corrected	2.45	2.82	3.43	3.87
B_a/B_N calculated	0.71	0.724	0.731	0.743

Equation 56

Another test of the same nature, but intended specifically as a check on equation 56, was made on a series of five 2,000-turn coils and at the single frequency of 10,000 cycles. These coils were each one inch long, they were layer wound but not layer insulated, and they were wound on wooden bobbins of 0.75-inch diameter.

A series resonance and substitution method was used to determine the effective resistance, using either 0.003 or 0.004 microfarad of a mica decade plus a variable air capacitor.

The following observations were made at 10,000 cycles:

Nominal wire diameter, mils	8.9	10.0	11.3	12.6	15.9
Outside coil diameter, inches	1.12	1.19	1.39	1.52	1.92
D-c resistance, ohms	55.5	54.1	44.8	39.3	29.2
R_{ac} by equation 8, ohms	71.6	63.9	59.8	53.8	93.0
R_{ac} measured, ohms	74.5	66.5	64.3	68.0	91.0

The measured value of R_{ac} includes a capacitor resistance correction arbitrarily figured for 0.001 power factor. This amounts to five ohms for the first three columns and seven ohms for the last two columns. Correction is necessary since the reactance/resistance ratio of some of the coils was above 60.

The round-wire diameter for minimum loss as determined from equation 56 is 0.0107 inch which is confirmed by the foregoing experimental result of 0.0110 inch.

Effect of Small Radial Depth of Winding

By way of emphasizing the inherent defects of the approximations used, in the absence of an external magnetic circuit and for the case in which the radial depth of the winding is small in comparison to the effective diameter of the coil, three coils of 2.375 inch inside diameter were wound from 0.010 round wire.

Data on the coils and measurements at 10,000 cycles follow:

Total turns	600	1,000	1,250
Number of layers	12	8	5
Coil length, inches	0.58	1.45	2.90
Radial thickness, inches	0.180	0.12	0.075
D-c resistance, ohms	41.8	69.0	84.7
R_{ac} by equation 8, ohms	42.4	70.2	85.2
R_{ac} measured, ohms	49.2	92.0	155

The same correction for capacitor power factor was made in the foregoing case as was made for the set of five coils.

It is obvious from the geometry of these coils that most of their eddy-current loss will result from the radial field when there is no external magnetic circuit, and so any method based on axial field losses only must be seriously in error.

End Loss in Spirals

Experimental work on small-scale spiral coils is complicated by the low impedances

involved, and the following account is not presented as being particularly conclusive, but rather as being the only experimental evidence available relative to equation 15.

A 60-turn spiral coil of electrolytic-copper ribbon 1 inch wide by 0.0035 inch thick was wound and the observations listed in Table II were made.

Measurements were made with parallel capacitances from 0.768 to 3.33 microfarads corresponding to frequencies from 10,380 to 21,660 cycles and substitution resistances from 89 to 203 ohms. The circuit was driven from the 125-ohm tap of the oscillator through a 500-ohm resistance. Results were calculated as shown in Table III.

The corrected values were arrived at by plotting on logarithm paper and drawing the best possible straight line to fit the points. Values of B_a/B_N were calculated from equation 15 as the curves of Figure 4 indicate that the maximum value of eddy-current loss would be about six per cent; these values substituted into equation 15 give the corrected end-loss factors. The value of B_a/B_N was measured with a 20-turn one-quarter-inch-diameter search coil, and the maximum that could be measured at 10,000 cycles was just under 40 per cent. This makes it seem questionable as to whether the actual value could have been as large as the 70-per-cent tabulated indication. The measuring method would be expected to give results that are substantially too small, and the corrected end-loss factor is too large as it includes both the axial-field loss and the capacitor loss.

Comparison With Literature

Equation 1 is equivalent to equation 12 of Field's[1] paper and to equation 27 of Bennett and Larson's.[6]

Equation 6 is a refinement of an equation given in the appendix of Summers' paper[5] and is equivalent to Taylor's[2] equation 3.

Equation 3 is exactly equivalent to an expression given by Lyon[3] for the loss factor in a one-coil-side-per-slot winding of N layers. To demonstrate this it is necessary only to expand the hyperbolic functions of complex arguments given there into the corresponding combination of hyperbolic and circular functions of real arguments. The latter form seems to be much easier to look up in tables, but the functions of complex arguments in this case are much easier to expand into series if the series is to be carried beyond the first positive exponent with a real coefficient.

Conclusions

The formulas presented here to measure the eddy-current resistance of coils with partial magnetic circuits (but excluding the losses in the iron) are equivalent to earlier formulas that have been reasonably well tested by a number of years' experience.

The extension of these formulas to coils wound from round wire and without an external magnetic circuit by the device of correcting for the end effect with a fictitious permeability and for the wire shape by using an equivalent square section seems to give results of usable accuracy, at least up to frequencies for which the eddy-current resistance is 50 per cent of the d-c resistance. This may be subject to a further limitation that the coil length should be at least as great as half the diameter. It will take more experimental work to establish such limitations definitely.

The extension of the original formulas to coils from ribbon conductors wound spirally to give a net effect of one or two turns per layer seems to be justified by the addition of another formula to calculate the end-effect loss as a separate item. While the end-effect formula cannot be regarded as satisfactory, in most practical constructions it will be possible to keep the end losses quite low simply by keeping B_a/B_N low, and it seems reasonable to expect that the end losses will be substantially smaller than the axial-field loss.

Another generally practicable method of keeping down the loss due to radial field is the construction shown in Figure 1; as long as the iron does not saturate, the

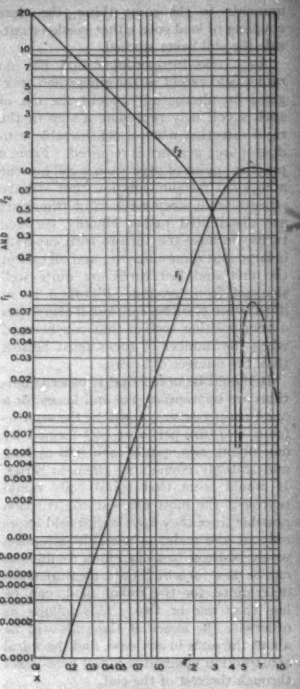

Figure 5. F_1 and F_2 plotted against x
Broken line indicates negative values

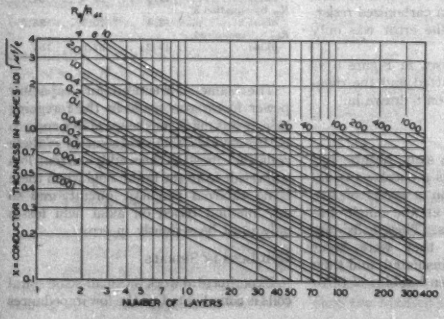

Figure 4. R_x/R_{dc} as a function of x and N, for the case that neglects the difference in length of layers and assumes arrangement of Figure 1A

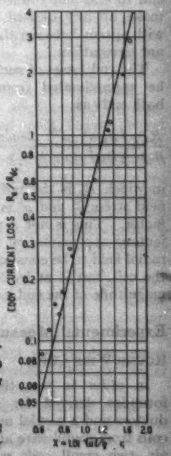

Figure 6. Eddy-current resistances plotted against x for round-wire coils
Circles are for long coil; dots are for short coil. Theoretical curve of equation 8 is solid line

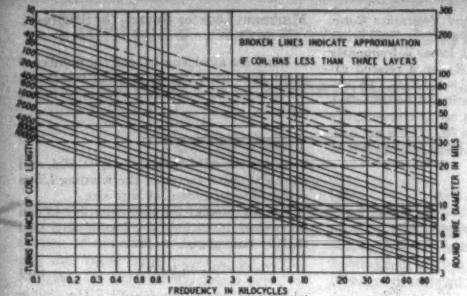
BROKEN LINES INDICATE APPROXIMATION
IF COIL HAS LESS THAN THREE LAYERS
TURNS PER INCH OF COIL LENGTH
ROUND WIRE DIAMETER IN MILS
FREQUENCY IN KILOCYCLES

Figure 7. Relation of frequency, turns per inch of coil length, and round-wire diameter for minimum loss

Taken from equation 57 with $\rho = 1.8$

radial field will approach zero as l_1 approaches l.

Certain formulas have been derived for determining conditions for minimum losses, and as these have been arrived at by conventional mathematical methods they seem certainly valid. The end losses of spiral coils have been ignored in these derivations, because the end losses are determined for the most part by coil proportions and not by layer thickness. These formulas are presented, not as requirements of logical design, but as a formulation of simple standards against which logical designs can be measured, and as exploring tools.

It should be noted that when the layer thickness of spiral coils is selected for minimum loss the total loss varies as $N^{-1/2}$. This relation is quite precise for $N>4$, and for $N=1$ the theoretical minimum of loss occurs for $x=3.14$ and is about eight per cent less than that determined by $N^{-1/2}$.

As a speculative item, the possibility is indicated of increasing the output of such equipment as transformers, while decreasing the amount of active material and increasing the efficiency, by the simple expedient of increasing the winding section in a direction perpendicular to the principal leakage flux. There will be of course cases in which such improvement is difficult or impossible.

Appendix

Practical units and inch dimensions are used throughout this paper except that ρ is in microhms per centimeter cube, and γ is in mhos per centimeter cube to correspond to customary usage in tables.

Notation is defined where first used, but for convenience those terms used more than once are defined below;

a_0 = radius of turn at zero leakage-flux density

a_1 = radius of turn at maximum leakage-flux density

A = area of layer at zero flux density, measured parallel to leakage

B = flux density at plane of dr in nth layer in lines per square inch

B_N = highest flux density associated with Nth layer in lines per square inch

B_Δ = increase in flux density per layer in lines per square inch

$C_1 = 1.935 m\rho 10^{-8}/\mu^2$

e = resistance drop per inch of periphery at plane of dr

f = frequency in cycles per second

$$F_1 = \left\{ \sinh x + \sin x - 2\left(\cosh \frac{x}{2} \sin \frac{x}{2} + \sinh \frac{x}{2} \cos \frac{x}{2} \right) \right\} / (\cosh x - \cos x)$$

$$F_2 = 2\left(\cosh \frac{x}{2} \sin \frac{x}{2} + \sinh \frac{x}{2} \cos \frac{x}{2} \right) \div (\cosh x - \cos x)$$

i = current density in amperes per square inch at dr

$k_1 = (n-1)/n$

$k_2 = (a_0 - a_1)/(N-1)a_0$

$k_3 = (a_0 - a_1)/2a_0$

$k_4 = (a_0 + a_1)/2a_0$

l = net conductor dimension in inches measured along leakage flux

l_1 = length of leakage-flux path in inches

l_2 = axial coil length in inches

$m = 0.505\,(\mu f/\rho)^{1/2}$

n = layer number counting from zero leakage-flux density

N = total number of layers in winding being studied

r = distance of plane of dr from high flux-density side of layer in inches

r_1 = thickness of layer in inches as measured across leakage flux

w = total loss in watts for one square inch of the flat surface of layer n

W = total loss in watts for N layers

$x = 2mr_1$

γ = conductivity in mhos per centimeter cube

δ = insulation thickness in inches

ρ = resistivity in microhms per centimeter cube

μ = fictitious permeability l/l_1 or lL/l_2L_1

R = resistance as denoted by subscripts; R_a/R_{dc} is proportionate increase in resistance due to end loss in both ends of spiral

L = actual inductance

L_1 = inductance calculated by long-coil formula (that is, without correction for end effect)

Derivation for Loss in Layer n

This part of the derivation is not new and so is presented in outline only. The method is simular to that of Bennett and Larson, in that the differential equation is set up for the flux density. This permits a direct substitution for the boundary conditions and a differentiation to determine current density.

It will be assumed that one side of a spiral coil is shown in section in Figure 1, and that the conditions are as set forth in the introduction. It will be convenient to take as the differential element of the conductor a piece one inch by one inch in the directions of current flow and leakage flux, with a thickness of dr inches measured across the leakage flux.

Let the voltage impressed on any particular layer of this spiral coil be E volts per inch of periphery, and let the induced voltage be e' per inch at the position of dr, a thin section parallel to the flat of the conductor and located r inches from that side of the conductor that is at the highest flux density. Then, if e is the resistance drop in volts per inch,

$$E + e' = e \tag{16}$$

If γ is the conductivity in mhos per centimeter cube, and i is the current density in amperes per square inch of conductor cross section,

$$2.54 e \gamma = i \tag{17}$$

Due to $i\,dr$, there is, in lines per square inch,

$$dB = 0.4\pi 2.54^2 e\gamma\mu\,dr = 8.1 e\gamma\mu\,dr \tag{18}$$

in which μ is the ratio of the leakage path to the net conductor along that path. If the difference in e' on the two sides of dr per inch of periphery is called de', then

$$de' = -j2\pi f B dr 10^{-8} = de \tag{19}$$

and from equation 18,

$$\frac{d^2B}{dr^2} = 8.1\gamma\mu\frac{de}{dr} \tag{20}$$

If we substitute from equation 19,

$$\frac{d^2B}{dr} = -j50.8 f\gamma\mu B 10^{-8} = -2jm^2 B \tag{21}$$

A solution of equation 21 is

$$B = A_1 \epsilon^{(1-j)mr} + A_2 \epsilon^{-(1-j)mr} \tag{22}$$

If n is the layer number counting from the region of zero leakage flux, the boundary conditions can be stated thus: when $r=0$, $B = B_n$; when $r = r_1$, $B = B_{n-1}$;

$$B_{n-1} = [(n-1)/n] B_n = k_1 B_n \tag{23}$$

If we eliminate A_1 and A_2:

$$B = B_n \frac{\left\{ \begin{matrix} k_1(\epsilon^{(1-j)mr} - \epsilon^{-(1-j)mr}) + \\ \epsilon^{(1-j)m(r_1-r)} - \epsilon^{-(1-j)m(r_1-r)} \end{matrix} \right\}}{\epsilon^{(1-j)mr_1} - \epsilon^{-(1-j)mr_1}} \tag{24}$$

$$\frac{dB}{dr} = B_n(1-j)m \frac{\left\{ \begin{matrix} k_1 \cosh mr \cos mr - \\ \cosh m(r_1-r) \cos m(r_1-r) \\ -j[k_1 \sinh mr \sin mr - \\ \sinh m(r_1-r) \sin m(r_1-r)] \end{matrix} \right\}}{\sinh mr_1 \cos mr_1 - j \cosh mr_1 \sin mr_1} \tag{25}$$

The rate of power loss per cubic inch of conductor in watts is

$$2.54\epsilon^2\gamma/2 \tag{26}$$

If the conductor is measured on one of its flat sides (parallel to principal flux) the loss per square inch of conductor is in watts:

$$\int_0^{r_1}\frac{2.54\epsilon^2\gamma}{2}dr=\int_0^{r_1}\left|\frac{dB}{dr}\right|^2\frac{dr}{51.6\gamma\mu^2}=w \tag{27}$$

Let

$$C_1=m/51.6\gamma\mu^2 \tag{28}$$

$$w=2mB_n{}^2C_1\times$$

$$\int_0^{r_1}\frac{\left\{\begin{array}{l}k_1{}^2(\cosh 2mr+\cos 2mr)+\\ \quad\cosh 2m(r_1-r)+\\ \quad\cos 2m(r_1-r)\\ -2k_1[\cosh mr_1\times\\ \quad\cos m(r_1-2r)+\\ \quad\cosh m(r_1-2r)\cos mr_1]\end{array}\right\}dr}{\cosh 2mr_1-\cos 2mr_1} \tag{29}$$

$$=B_n{}^2C_1\frac{\left\{\begin{array}{l}(k_1{}^2+1)\ (\sinh 2mr_1+\sin 2mr_1)-\\ \quad 4k_1(\cosh mr_1\sin mr_1+\\ \quad\sinh mr_1\cos mr_1)\end{array}\right\}}{\cosh 2mr_1-\cos 2mr_1} \tag{30}$$

$$=B_n{}^2C_1\{(k_1{}^2+1)F_1+F_2/n^2\} \tag{31}$$

in which F_1 and F_2 have the meanings defined under notation.

Now let the increment of flux density per layer

$$B_n/n=B_\Delta \tag{32}$$

$$wA=B_\Delta{}^2C_1A\{(2n^2-2n+1)F_1+F_2\} \tag{33}$$

Total Loss for N Layers

$$\Sigma wA=W$$

$$=B_\Delta{}^2C_1A\{F_1\sum_1^N(2n^2-2n+1)+NF_2\} \tag{34}$$

$$W=B_N{}^2C_1A\{F_1(2N^2+1)/3+F_2\}/N \tag{35}$$

It will be found that for $x<2$ the foregoing expression can be closely approximated by writing the series expansions for F_1 and F_2 to include the first term in x with a positive exponent. If we make this substitution,

$$W=B_N{}^2C_1A\{x^2(5N^2-1)/360+2/x\}/N \tag{36}$$

Correction for Differences in Layer Lengths. In the foregoing two equations no account has been taken of the difference in periphery of the various layers of a spiral coil. As the area of the layer at zero leakage-flux density has been taken as A, the area of any other layer will be $A\ [1-(n-1)k_3]$, where $k_3=(a_n-a_1)/(N-1)a_0$; a_0 is the length of the layer at zero flux density, and a_1 is the length of the layer at maximum flux density. Then:

$$W=B_\Delta{}^2C_1A\{F_1\sum_1^N(2n^2-2n+1)\times$$

$$[1-(n-1)k_3]+F_2\sum_1^N[1-(n-1)k_3]\} \tag{37}$$

$$=\{B_N{}^2C_1A/N\}\left\{F_1\left(\frac{2N^2+1}{3}-\right.\right.$$

$$\left.\left.\frac{3N^2+N+1}{6}\frac{a_n-a_1}{a_0}\right)+F_2\frac{(a_0+a_1)}{2a_0}\right\} \tag{38}$$

Effective Resistance and Resistance Ratio. The most useful form in which to have information on eddy-current losses is frequently an expression for R_{ac}/R_{dc} or a related expression $(R_{ac}-R_{dc})/R_{dc}=R_e/R_{dc}$. To obtain such an expression it will be necessary to state the d-c loss in terms conveniently comparable to equation 36. If l is net conductor width measured along leakage flux in inches,

$$R_{dc}=NA(a_0+a_1)/5.08r_1l^3\gamma a_0 \tag{39}$$

$$\text{D-c loss}=\frac{B_N{}^2A}{25.8\gamma\mu^2Nr_1}\frac{a_0+a_1}{2a_0}$$

$$=\frac{4B_N{}^2C_1A}{Nx}\frac{a_0+a_1}{2a_0} \tag{40}$$

Since for a given value of B_N and ignoring eddy-current losses the a-c loss will be one half of the d-c loss, this a-c loss may be called W' and then $R_{ac}/R_{dc}=W/W'$. If layer length differences are neglected,

$$W'=2B_N{}^2C_1A/Nx \tag{41}$$

$$R_{ac}/R_{dc}=x^4(5N^2-1)/720+1 \tag{42}$$

Determination for Minimum Loss With Dimension h Restricted

To determine the layer thickness for minimum loss when dimension h is restricted, it is expedient to make the usual series approximations for F_1 and F_2 in equation 38 that are quite accurate for $x<2$, and to assume that $N>3$, so that the loss equation becomes

$$W\approx B_N{}^2C_1A\left\{\frac{x^2N}{72}\left(1-\frac{3}{2}k_2\right)+\frac{2}{Nx}(1-k_1)\right\} \tag{43}$$

Since

$$N=2mh/(x+2m\delta)$$

$$W\approx B_N{}^2C_1A\left\{\frac{hm}{36}\left(1-\frac{3}{2}k_2\right)\left(x^2-2mx\delta+\right.\right.$$

$$\left.\left.4m^2\delta^2-\frac{8m^2\delta^3}{x+2m\delta}\right)+\left(\frac{1}{mk}+\frac{2\delta}{kx}\right)(1-k_1)\right\} \tag{44}$$

$$\frac{dW}{dx}=B_N{}^2C_1A\left\{\frac{hm}{36}\left(1-\frac{3}{2}k_2\right)\left(2x-2m\delta+\right.\right.$$

$$\left.\left.\frac{8m^2\delta^3}{(x+2m\delta)^2}\right)-\frac{2\delta}{kx^2}(1-k_1)\right\}=0 \tag{45}$$

$$\frac{1-\frac{3}{2}k_2}{1-k_1}\frac{k^3m^3x^4}{18}\frac{x+3m\delta}{(x+2m\delta)^2}=2\delta \tag{46}$$

$$\frac{3k_1-1}{2k_1}k^3m^4r_1{}^3\frac{(1+3\delta/2r_1)}{(1+\delta/r_1)^3}=\frac{9\delta}{2} \tag{47}$$

$$\frac{r_1{}^3}{\delta^3}\frac{1+3\delta/2r_1}{(1+\delta/r_1)^3}=\frac{9}{2\delta^3k^3m^4}\frac{2k_1}{3k_1-1} \tag{48}$$

$$\frac{r_1}{\delta}=q=\sqrt[3]{\frac{9}{2\delta^3k^3m^4}\frac{2k_1}{3k_1-1}} \tag{49}$$

$$r_1\approx\delta\left(0.17+\sqrt[3]{\frac{9}{2\delta^3k^3m^4}\frac{2k_1}{3k_1-1}}\right) \tag{50}$$

when $r_1/\delta>1$

Minimum Loss for Round- (or Square-) Wire Coils

When the axial length l_1 and the number of turns t are fixed, the number of layers is a function of the diameter d of round wire, so that

$$N=tr_1/l=tx/2ml \tag{51}$$

in which the only variable is $r_1=0.89d$, and the axial space factor of the winding l/l_1 is assumed independent of wire size.

For the present purpose equation 43 can be revised to include d-c loss if any, and slightly rearranged, so that

$$W\approx U(x^3N/72+4k_4k_2/NX) \tag{52}$$

where

$$k_4=1-2a_1/(a_0+3a_1)$$

and

$$U=B_N{}^2C_1A\,(1-3k_2/2)$$

Substituting from equation 51

$$W\approx U(x^4t/144ml+8k_2k_4ml/tx^2) \tag{53}$$

$$dW/dx=U(x^3t/36ml-16k_2k_4ml/tx^3)=0 \tag{54}$$

$$x=2.88(k_2k_4)^{1/6}(ml/t)^{1/3} \tag{55}$$

$$r_1=1.44(k_2k_4)^{1/6}(l/m^2t)^{1/3}$$

$$=2.27(k_2k_4/K^3)^{1/6}(\rho l_1/ft)^{1/3} \tag{56}$$

since

$$m^2=0.254fK1/l_1\rho$$

in which K = Nagaoka's constant.

If there is no d-c loss $k_2=1$; $(k_4/K^3)^{1/6}$ usually will exceed unity by not more than a few per cent. Then if $\rho=1.8$ for copper,

$$d=r_1/0.89=3.11/(ft/l_1)^{1/3} \tag{57}$$

In this equation d is the round-wire diameter for minimum loss, and r_1 is the square-wire diameter for minimum loss, provided that $N>3$. The approximation is fair for $N=2$.

It is interesting to note that the wire diameter for minimum loss is independent of the axial space factor (assumed constant) except as this influences K and k_4.

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Lightning Arresters for Distribution Apparatus

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THERE are today two general types of lightning arresters in use for the protection of distribution apparatus. They are the valve type covered by AIEE Standard 28, and the expulsion type, for which AIEE Standards are being formulated. Both have been used widely for many years. Typical specimens are illustrated in Figure 1. The valve type is the older. The first distribution-valve arrester was an Autovalve produced in 1922. The first expulsion-type distribution arrester was the deion arrester (United States Patent, 2,050,397) used on surge-protected distribution transformers in 1931. By far the largest number of expulsion-type arresters manufactured have been applied as part of completely self-protected transformers. Many of these have used a somewhat different physical construction and mounting as shown in Figure 2 than that used for the arresters installed separately from the transformers. There exist today several variations of both the expulsion and valve types.

With so many years of service behind the two types, the question arises why both still persist. Why has not the industry decided that one is better and discarded the other? Why do some manufacturers make both types, and some only one? Affiliated with a company that manufactures both types, the authors frequently are asked, not only by users but also by associates in the company, why the company does not eliminate one of them and concentrate on the other. From a manufacturing standpoint this would be a highly desirable simplification, but the reason why both are made is that there are demands for both. Apparently the industry is not ready to accept only one in lieu of both.

A brief review of the history that stimulated the two types is of passing interest. There were two major reasons for the development of the expulsion type to parallel the valve type. These were radio broadcasting and the growth of rural electrification.

Valve-type arresters in the 1920's were contemporary with the growth of radio broadcasting into a public service. In those days the valve arresters were frequent causes of radio interference as a result of moisture collecting inside of them. Methods of testing for radio interference were not developed, and arresters were not designed to avoid it as it was not a known requirement. It soon became evident, however, that it was a very important requirement. Many engineers believed that it was impossible to seal an arrester against moisture entrance and that an arrester should be thoroughly ventilated. The expulsion arrester is such a device, and this was then greatly in its favor. At the present time radio interference is hardly a worry in either valve or expulsion arresters since methods of sealing and testing valve arresters have been devised that effectively prevent moisture collection. Autovalve arresters manufactured since 1932 have been signally free from moisture or radio interference.

Most expulsion-type arresters, because of the requirement of clearing appreciable power-follow currents, inherently possess a high degree of ability to discharge severe lightning current without damage to themselves. In this respect they surpass the early valve types. The importance of surge capacity became more apparent as rural electrification proceeded. It might be said that the appearance and the successful operation of the expulsion-type arrester threw a challenge to the valve type which resulted in a general increase in quality of both types of arresters. This is a healthy condition, consequently, it is well that the industry has not yet settled on one type to the exclusion of the other.

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The Functions of Lightning Arresters

Fundamentally lightning arresters, regardless of type, must perform the same function, to provide by-passes around insulation. When lightning strikes a circuit, transient currents flow in the system. With these currents are associated potentials that are functions of the current and the impedance to the current flow. If the flow of lightning current is not obstructed by impedance or insulation, the voltages between points that are electrically adjacent in the circuit are small, but, if the flow is obstructed, very high voltages may appear, because the lightning current puts forth all its effort to flow. If the obstruction consists of insulation, the voltage developed across it may be sufficient to puncture or flash around it, thereby giving the current a means of continuing by way of damage or outage. A lightning arrester provides an easy path for the lightning current to get around the insulation so that high voltages will not develop. The by-pass, however, must be such that it does not interfere with the supply of power to users. This means that, when operating conditions are normal with no surges on the system, the arrester must be an insulator, so that it prevents flow of power current. When a transient voltage appears which might exceed the insulation strength of the apparatus to be protected, the arrester must become as quickly as possible a good by-pass for lightning current. After the release of this current, the by-pass must transform itself back to its insulation condition so quickly that no circuit breakers or fuses in the circuits are called upon to open in order to interrupt flow of system current through the arrester.

A lightning arrester may be looked upon as a very fast circuit breaker connected from line to ground, normally open, but

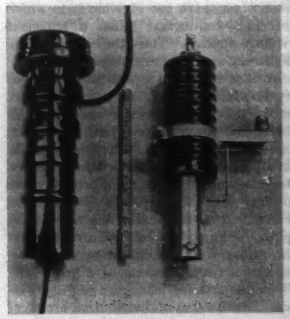


Figure 1. Typical distribution lightning arresters of the valve and expulsion types

Rating, nine kilovolts

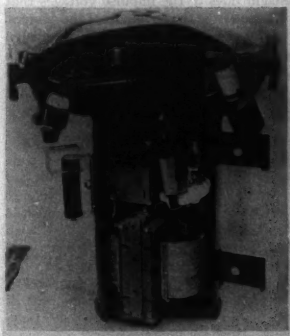
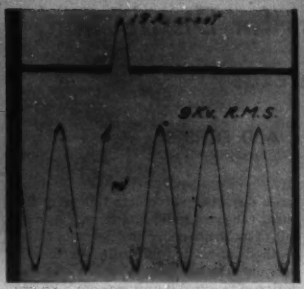


Figure 2. Completely self-protected distribution transformer with internally mounted expulsion-type arresters

(a). Autovalve arrester. Upper trace is 60-cycle voltage. Lower trace is power-follow current. Crest of follow current is 36 amperes. Current limited by valve element only as apparent from uniformity of voltage wave



(b). Delon arrester. Lower trace is 60-cycle voltage. Upper trace is follow current limited by circuit

(c). Delon arrester. Follow current higher than in b. Short-circuit current of test circuit was 10,000 amperes rms. Arrester limits follow current

Figure 3. Typical oscillograms of power-follow currents and their interruption for valve and expulsion arresters

Arrester ratings, nine kilovolts
Power voltage used in tests, nine kilovolts rms

one which closes immediately at a predetermined voltage and reopens quickly after the disturbances have passed. The closing mechanism in the lightning arrester is a spark gap of some form which becomes conducting when a transient voltage appears. Thus, the circuit for the lightning current is established, but this circuit is then also a path to ground for system fault current. Arresters therefore must incorporate a contrivance that will open this power current path or aid the spark gap to reopen it. Simple gaps, such as rod gaps, are not classed as arresters, because, although they will provide more or less effective by-passes for lightning currents, they are unable to interrupt the path. Their power-follow currents must be cleared from the circuit by the operation of a circuit breaker or a fuse. The lightning arrester takes care of this by itself. Both types of distribution arresters accomplish the closing and reopening of the relief circuit in essentially the same fashion. The differences lie principally in the process involved in re-establishing the insulation of the arrester and in the magnitudes of the impulse voltages that appear across the terminals of the devices.

The simplest analogy to the expulsion type of arrester is that it is like a fuse with the fuse link omitted. It consists essentially of a tube, usually of fiber, with electrodes in each end. In series with this is a spark gap. When a high voltage occurs, the series gap and the gap in the tube spark. By this process a circuit is made through the tube just as if a fuse link had been present. The arrester thus becomes a path of low impedance, and the surge voltage across the terminals drops to a low voltage after spark-over. This voltage drop consists only of the arc drop in the extinction chamber. Therefore, as far as power-follow current is concerned, the device may become nearly a short circuit. However, like the fuse, it interrupts the system fault current when its current wave passes through zero because of the gas evolved by the heat of the arc from the walls to the extinction chamber. Unlike the fuse, it does not have to be refilled, because it has no fuse link. The expulsion-type arrester operates repeatedly without attention. The devices are so designed that their spark-over is sufficiently low to provide protection for the apparatus or insulation they are intended to protect. In some recent constructions for use on distribution circuits, there are incorporated features that produce appreciable arc voltage while power current flows, so that the power current follow is determined partly by the device and partly by the system characteristics. This arc voltage may be an appreciable part of the normal circuit voltage, but compared to the spark-over voltage it is small.

The expulsion arrester thus performs the cycle required of a lightning arrester. It is normally an insulator, it becomes a conductor of low impedance when necessary to prevent high voltage, and it interrupts the system current quickly and reverts to an insulator. Its operation does not interfere with the flow of power in the system.

A familiar analogy for the valve type of arrester is not so easily found, unless it be likened to an automatic valve that opens and closes as circumstances require. The valve arrester, too, has a spark gap which normally provides insulation and operates as a switch to close by sparking when a surge voltage appears. Unlike the expulsion arrester, the series gap in the valve arrester also must reopen the circuit after the necessity for limiting the voltage has passed. Simple air gaps are not capable of interrupting high currents such as might be involved in system faults. Gaps such as are used in valve arresters can interrupt reasonably high alternating currents, of 50 to 100 amperes, but not much more. Therefore, to insure successful operation of the device, the power-follow current that flows after the lightning discharge must be limited to a magnitude that the gap can interrupt. This can be accomplished by series resistance. However, if this is the common type of constant resistance and of such a magnitude that it will limit the power-follow current to the afore-mentioned value when system voltage only is impressed across its terminals, then when high lightning currents flow the IR drop will be large. This would impress high voltage on the insulation supposedly protected. An example, would be a nine-kilovolt arrester with a constant series resistance that will limit the current at nine kilovolts to 100 amperes. If a surge current of 2,000 amperes flows through it, it will develop 20 times normal voltage or 180 kv. Such a device would be inadequate for purposes of lightning protection. For this reason the series impedance used in valve arresters is of a special kind that has a high effective resistance at low voltage and a low effective resistance when high currents flow. It is for this reason that they are called valve elements. The impedance or the valve opening regulates itself to the flow of current and limits the voltage. The regulation in most valve elements is a property of the electrical contacts between the particles of which it consists. If we choose to think of the valve element as a resistor, then in a 3,000-volt valve-type arrester its apparent resistance at 3,000 volts may be 100 or more ohms, whereas when it is passing 50,000 amperes of surge current its apparent resistance may be less than half an ohm.

By the co-operative functioning of the series gap and the valve element, the valve type also performs the functions expected of an arrester. It is normally an insulator, it becomes a path of relatively low impedance, and it re-establishes itself as an insulator after the lightning

discharge has passed. It does not interfere with the flow of power in the system.

The principal difference in the operation of the two types of arresters is in the way in which they dispose of the system follow current. In the valve arrester the follow current is limited by the device itself regardless of system capacity. Valve arresters, therefore, are rated only on the basis of voltage. The rating defines the maximum voltage applied across the arrester terminals against which the arrester can return itself to an insulator subsequent to a surge discharge. In the expulsion arrester the follow current may be determined principally by the system and these devices generally are rated in both voltage and current somewhat like fuses. As far as service is concerned, the difference between the two is not significant because either device, as shown by Figure 3, operates without causing what is generally termed a fault.

Protective Characteristics

The most important quality that an arrester should possess is the ability to protect insulation against high voltage. The magnitudes to which it limits surge voltages are related in various ways to the power voltage which the arrester is able to clear.

Valve and expulsion arresters both provide surge protection for distribution apparatus. This can be seen by comparison of the impulse characteristics of the arresters with the standard impulse levels of the equipment. The major use of distribution lightning arresters is to protect distribution transformers against damage to their insulation or flashover with consequent outage. A ready means of comparison is found in the relation of the lightning-arrester characteristics to the impulse withstand tests required of transformers. The transformer manufacturers have, in the National Electrical Manufacturers Association Transformer Standards stated certain impulse voltages which the transformers covered by these standards are able to withstand without damage. The test voltages are described and coordinated with the insulation class designations of the transformers as in Table I They provide a definition of the impulse strength of transformers and thus a means of relating the lightning protection to them directly. Present AIEE Standards for valve arresters specify a number of tests which are complete and possibly more voluminous than necessary to furnish the industry with adequate information of the characteristics of these protective devices. The tests described in lightning-arrester standards are not related directly to the withstand impulse-voltage tests specified for transformers, although their relation can be determined by reference to curves. A simple and complete comparison between transformer-insulation strengths and the degree of protection provided by arresters can be made by applying to the arrester the withstand test voltages specified for those transformers with which the arresters may be used. If the arrester, when subjected to this test voltage, prevents voltages of the magnitude and character of the withstand voltages from developing, it is obvious that the transformer is protected by the arrester. The relation between transformer strength and arrester performance for a typical application is shown by the oscillograms of Figure 4. The 15-kv insulation class transformer and the nine-kilovolt arresters, a common combination, are illustrated. In order to show both the arrester impulse spark-over characteristics and the effect of voltage drop while the arrester carries current, two sets of oscillograms are shown with different time scales.

Impulse Spark-Over Voltages

Figures 4a and b show the arrester spark-over characteristics in relation to the transformer withstand voltages. In Figure 4a the trace marked 96 kv is the 1.5x40 wave which the transformer withstands if it meets NEMA Standards. If a nine-kilovolt expulsion arrester of the type illustrated in Figure 1 is connected in the test circuit and the transformer withstand voltage applied, spark-over of the arrester occurs at 69 kv. The nine-kilovolt valve arrester shown in Figure 1 sparks at 52.5 kv. Both of these are well below the full-wave voltage that the transformer will withstand.

The response of arresters to the chopped wave used for transformer testing is practically the same as in the case of the full wave. Therefore, it has not been shown. Of interest, however, would be the arrester behavior on a front of wave test for the transformer, because this would have an appreciably faster rate of voltage rise. Such front of wave tests have not been standardized for distribution transformers. An approximate value, which might in the authors' opinion be used, is shown in Figure 4b by the broken-line trace marked 165 kv. Such a test wave applied to a nine-kilovolt deion arrester causes spark-over at 113 kv and on the nine-kilovolt Autovalve arrester at 57 kv. Again, both of these values are well below the impulse voltage that can be impressed on a transformer without damage. It should be

Figure 4. Relation between transformer impulse withstand voltage (see Table I) and arrester voltages

Transformer insulation class, 15 kv
Arrester ratings, nine kilovolts

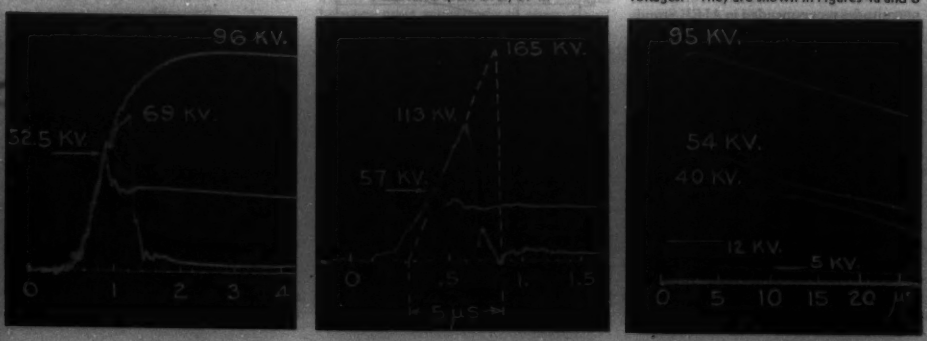
(a). Transformer full wave, 96 kv. Deion arrester spark-over, 69 kv. Autovalve spark-over, 52.5 kv

(b). Transformer assumed front of wave test, 165 kv. Deion arrester spark-over, 113 kv. Autovalve spark-over, 57 kv

(c). Transformer full wave, 95 kv. Voltage across arresters during discharge of specified surge currents:

Deion arrester, 20,000 amperes, 12-5 kv
Autovalve arrester, 5,000 amperes, 40 kv, 20,000 amperes, 54 kv

These oscillograms do not show the spark-over voltages. They are shown in Figures 4a and b



noted from the comparison of Figures 4a and b that the transformer will withstand a higher voltage, if applied for only a short time, than the full 1.5x40 wave test voltage.

Figure 4 indicates that the impulse spark-over voltage of the expulsion arrester is higher than that of the valve arrester. In the expulsion arrester, spark-over takes place over two air gaps, the series gap, and the gap in the extinction chamber. The gap in the extinction chamber is relatively long to insure clearing of the power-follow current, and the time lag curves of spark-over, Figure 5, indicate that the spark-over voltage increases with decreasing time to spark-over. This is not serious since insulation time-lag curves have somewhat the same shape. Although the spark-over characteristics can be modified by means such as the electrostatic shielding used in the arrester shown in Figure 1, the foregoing factors in general fix the order of impulse spark-over voltage.

The gap in the valve arrester is not called upon to interrupt high power-follow currents, as their magnitude is limited by the valve element. Therefore, it can be made with low spark-over voltage and with time-lag characteristics that resemble those of sphere gaps which are more or less flat and begin to turn up only at very short times to spark-over as illustrated in Figure 5. Although there is this difference between the spark-over voltages of the valve and expulsion types, Figure 4 shows that there is ample margin between the transformer impulse strength and the impulse spark-over of either arrester.

Voltage During Discharge

More than the impulse spark-over should be taken into account in the correlation between transformer strength and protective characteristics of the arrester, because, while the arrester is discharging surge current, some voltage exists across its terminals as the result of arc or impedance drops. In Figure 4c are shown these voltage characteristics of both types of arresters for several discharge currents of magnitudes recommended in AIEE Standards. These again are related to the transformer full-wave withstand voltage shown again in Figure 4c by the trace marked 95 kv. The spark-over voltages of the arresters are not apparent in Figure 4c because of the larger time scale. The spark-over voltages are shown in Figures 4a and b.

Consider the valve arrester characteristics. The trace marked 54 kv is the voltage developed across the arrester during discharge of a 20,000-ampere test surge. The trace marked 40 kv is the voltage across the arrester with a test current of 5,000-amperes crest. It should be noted that the voltage across the valve arrester drops from the crest reached after a few microseconds. It is sometimes thought that the voltage drop of the valve arrester persists at its crest magnitude for the duration of the discharge. This is not the case, especially when high currents are involved.

The voltage that exists across the expulsion arrester while discharging 20,000 amperes is shown by the lowest trace in Figure 4c. Immediately after discharge, the voltage collapses to 12 kv and then drops further, until after several microseconds it has decayed to five kilovolts. For the expulsion arrester, the voltage for a 5,000-ampere discharge is not shown. It is less than that for 20,000 amperes. It is apparent that the discharge voltages of the expulsion arrester are appreciably lower than those for the valve arresters. However, in either case, there is considerable margin between the withstand voltage of the transformer and the voltages developed across either arrester during the discharge of surge current. These differences are thus not of practical importance, although they sometimes arouse controversy. The valve arrester becomes conducting on steep impulse voltages at lower values than the expulsion type. One might say that this is an advantage. On the other hand, the voltage across the expulsion arrester collapses to a lower value once discharge has begun. This is an advantage in favor of the expulsion arrester.

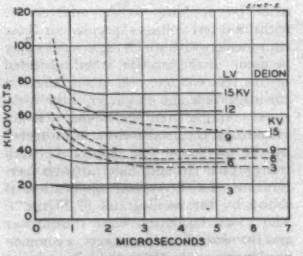


Figure 5. Impulse spark-over time-lag characteristics of distribution arresters of the valve and expulsion types

Full lines—Autovalve arresters
Broken lines—Deion arresters
Numbers on curves indicate voltage rating

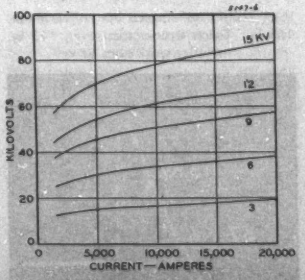


Figure 6. Relation between crest of 10x20-microsecond discharge current and crest of voltage developed by the current for Autovalve arresters

Numbers on curves are arrester ratings

The important impulse characteristics of both arresters are shown in curve form in Figures 5 and 6. As far as transformers manufactured during the last decade or so are concerned, either device is adequate. This is particularly true on completely self-protected transformers where the manufacturer has a known insulation strength with which it is relatively easy to co-ordinate the arresters. On very old transformers the impulse strength may be lower, as they were not built to meet present standards. For the protection of such transformers, the valve arrester may be preferable because of its lower sparking voltage. It is true that with very heavy current discharges the voltage developed across the valve arrester during the discharge may exceed the impulse strength of the old transformer, so that the transformer will not be protected under these conditions. For example, when discharging a surge current with a crest of 65,000 amperes, the peak voltage across a nine-kilovolt valve arrester may be 70 kv. Though this is well below the full-wave strength of a recent transformer that meets Table I, it may well exceed the strength of a very old transformer. However, the occurrence of such heavy currents is rare. Field measurements of the surge currents discharged by arresters in rural service indicate that 50 per cent of the operations involve currents of less than 1,500-amperes crest and 96 to 98 per cent less than 20,000 amperes. By and large, therefore, valve arresters should give better protection to the old transformers being considered. On the other hand it is probably desirable that transformers with such low-impulse strengths be replaced by modern ones.

Surge-Current Capacity and Life

An arrester fundamentally is intended to prevent service outages during thunder storms. Therefore, it should not only prevent insulation failures as far as possible but also should be rugged to prevent damage to itself. Electrical damage may result from very severe lightning—after all a distribution arrester is a device of only modest size—or it may result from a temporary system voltage condition in excess of the arrester rating or because of a defect in the arrester. Any of these is possible. Considering the effects of lightning, it is desirable that the arrester have surge discharge capacity sufficient to

Table I. Impulse Insulation Withstand Tests for Distribution Transformers (Oil Immersed)

Insulation Class, Kilovolt Rms	Transformer* Voltage Rating	Chopped Wave			Full-Wave Voltage, Kilovolt Crest	Arrester** Voltage Rating, Rms
		Voltage, Kilovolt Crest	Minimum Time to Flashover, Microseconds			
2.5		54	1.25		45	
5.0	2,400	99	1.5		60	3,000
8.66	4,800	88	1.6		75	6,000
15.0	7,200	110	1.8		95	9,000
15.0	13,200	110	1.8		95	15,000

*These are usual standard ratings and usually fall into the insulation classes shown. The insulation class indicates the insulation strength.

**These are the arrester ratings usually used with the transformers listed in column 2. In some cases because of circuit conditions, other arrester ratings may be used with a given transformer rating.

Test voltage wave shape is 1.5x40 microseconds (1.5 microseconds from 0 to crest, 40 microseconds to half of crest).

Full-wave test is an application of the full unmodified 1.5x40 wave to the test specimen. (See Figure 4a.) In the chopped-wave test, a 1.5x40 wave shape is applied, but the test voltage is removed or chopped by flashover of a properly set parallel gap in the time specified in the table.

In front of wave tests, the voltage applied to the test specimen is removed or chopped by a gap in a specified time, but while the test voltage is still rising. (See Figure 4b.) Front of wave tests for distribution transformers have not yet been determined.

This table is based on Table V of NEMA Transformer standards, publication 42-73. For more complete data, refer to those standards.

Table II. Comparison of Delon and Autovalve Lightning Arresters for Distribution Apparatus

Characteristic	Type of Arrester	
	Delon	Autovalve
Impulse spark-over, 0.5 microsecond	Lower	
Voltage during discharge	Lower	
Power-follow current		Less
Surge-current capacity:		
65,000 amperes	Same	Same
Long low currents	Better	
Service life	Comparable	Comparable
Construction	Open	Sealed
Series gap	Integral part of arrester	
Is series gap setting critical	No	Sealed
Is application affected by system recovery voltage	No*	No*
Is application limited by system fault currents	No**	No
Is co-ordination of feeder relaying or fusing and arrester required	Usually not	
Does operation depend on expenditure of material	Refer to text	
Does system frequency affect arrester application	***	****
Is arrester applicable to delta systems	Yes	Yes
Radio interference	No	No
Line lockouts	No	No

*Theoretically yes, practically no. Experience shows that either type operates satisfactorily on existing distribution circuits.

**Holds for the arrester described in text.

***Ratings are based on 60 cycles.

****Ratings are based on 25–60 cycles.

minimize the chances of arrester damage by lightning in the field. Experience has developed a basis of test for the distribution arrester. This is the 65,000-ampere test recommended in the AIEE Standards. Years of experience with arresters of various surge current capacities indicate that capacities of less than 65,000 amperes will engender unsatisfactory rates of failure from lightning in the field. The 65,000-ampere test is thus a reasonable index to the ability of arresters to weather severe storms. Both of the arresters shown in Figure 1 meet this criterion, and field experience with both has been excellent.

The dangers of system overvoltage are well known. A valve arrester is sensitive to the system voltage impressed on its terminals during the clearing period. In fact excessive system voltage may be called its chief enemy. It is not in general sensitive to rate of system recovery voltage, because it itself determines the rate of recovery voltage across its series gap as a result of the effective resistance of the valve element. However, if the system voltage exceeds the arrester rating, the gap may not be able to clear and the arrester may be damaged.

The ability of the expulsion arrester to interrupt depends on several factors besides voltage, such as the rate of recovery voltage, overshoot of recovery voltage, current to be interrupted, and on the power factor of the circuit. When any of these conditions are not as severe as those for which the arrester is designed, an additional margin in interrupting ability results. It is not recommended, however, that a lower voltage arrester be used because of any margin of this type. The voltage rating should be considered a maximum rating.

A very live question to which a direct answer is difficult involves the life of an arrester. How long should it last, and how long may the various types be expected to last? Laboratory tests and records of discharges through arresters in actual service give clues on the basis of which estimates may be made, but the best indication is experience. This may appear unfair to the user, because he is the one that has to acquire the experience. Fortunately, the art is now in a phase where considerable experience has been accumulated.

Discharges of appreciable magnitude combined with the arrester's normal power follow will have little effect on the ability of the valve arrester to function for many operations. The impulse protective characteristics of the valve arresters of Figure 1 are not affected by high discharge currents. Repeated discharges of currents of 20,000 amperes or more exert some effect on the valve material which ultimately will cause it to puncture. With the 65,000-ampere surge-capacity test, a few repeated discharges may damage the arrester. The test current that will destroy a distribution arrester with the first shot may be considerably higher. The duration of the discharges also has a bearing on life. There is no doubt a relation between crest magnitude of current and shape and duration of wave tail on the one hand and the number of discharges an arrester will withstand on the other. This relation is not well known. Something is known of the high-crest short-duration effects and something is known of the low-current long-duration effect as shown by the 1/2 to several cycles of normal power follow current that the arrester may withstand. Between these is a range that is not determined because of the tedious labor and the expense that would be involved in establishing it. The lack of this information is not serious as indicated by the low rate of damage in the field to modern distribution arresters of either type.

The expulsion arrester wears. Expenditure of material is the principle upon which it operates to interrupt power-follow current. The wear caused by surge current is on the whole small. An excessively high surge current may burst the device or crack it, but this is the exception. The principal cause of wear in an expulsion arrester is the follow current that it must interrupt. The degree of erosion is a function of the magnitude and the duration of the follow current, and this again depends to some degree on the system characteristics and the relation of the timing of the surge discharge with respect to the phase of the system voltage. The factors that affect erosion are so variable that it is difficult to evaluate wear in terms of years of service. The expulsion arrester has been in use for some 13 years as part of the *SP* and *CSP* transformers. Neglecting causes of damage other than lightning, the life, measured in annual percentage of arresters damaged, obtained from the deion arresters used on those transformers as well as from deion arresters used as separately mounted devices actually has been better than secured from the comparable Autovalve arrester. This would indicate that the erosion effect of power-follow current, which can be accentuated by specific test conditions, is not the complete determi-

nant of service in years. There is further corroboration of this by the fact that lightning field studies have indicated that a lightning arrester on any given distribution transformer in rural service discharges on an average of about once a year, but that over a period of years the number of discharges in any year may vary between zero and eight. Further, as already mentioned, power follow in expulsion arresters depends on how the surge and the 60-cycle power voltage overlap. In many cases there will be no power follow at all, and it is found in laboratory testing that the conditions of timing must be controlled carefully to obtain the worst power-follow conditions. Moreover, heavy discharge currents in themselves often cause the evolution of sufficient gas from the walls of the extinction chamber to prevent power follow. Although tests can be made which will show a longer life, in number of operations for valve arresters than for expulsion arresters and vice versa, it is logical to expect that both arresters will give comparable years of satisfactory service. Experience appears to bear this out. It may be that within certain ranges of lightning-discharge wave shape and magnitude the effect of the surge alone is less marked on the expulsion arrester than it is on the valve type.

Some weight should be given to the consideration that practically all makers of self-protecting distribution transformers employ expulsion arresters for protection. They have had excellent experience with their choice. On the other hand for separately mounted arresters the activity on valve-type distribution arresters exceeds that of expulsion arresters.

Physical Differences

As the operation of the expulsion arrester generates gas which must be vented, it must be more or less open in construction. This has advantages in the eyes of many users and designers and is something not readily feasible in valve arresters.

Most valve arresters do not generate gas, nor do they have to handle high power-follow currents. Therefore, total enclosure is feasible, thereby protecting the parts from the weather and avoiding any exposed line or ground terminals or leads. This in turn is regarded as an advantage by many users, and it is something not readily done with expulsion arresters.

Effect on Operation of Primary Fuses

Recently some statements have been made that the collapsing voltage of the expulsion arrester has a distinct advantage in that it will permit fewer primary fuse operations. In brief, the reason given for this is that the expulsion arrester, because of this voltage collapse, exposes the transformer to less voltage for the duration of the discharge than the valve type, and, therefore, there is less tendency for lightning current to penetrate through the transformer winding and the fuse. There is clearly a difference in these voltages; however, if all of the factors that enter into the problems of fuse operation are considered, so broad a statement hardly is warranted. The subject is complex and beyond the scope of this paper. It should be explored further. If fuse operations can be decreased by the use of a certain type of lightning arrester, that is important, and it is to be hoped that experience of operating engineers in this connection may be presented to the Institute.

Special Application

There is one application in which there exists a definite preference. It is an application which requires both types of arresters to supplement each other and is, therefore, a good case. It is the protection of rotating machines. This subject is covered elsewhere.[1] In this application arresters must be used at the terminals of the machine and arresters also must be used at some point on the line removed from the machine terminals. The arresters at the machine terminals definitely must be of the valve type, because they spark at low voltages and because the voltage does not collapse after spark-over. For the arresters on the line, however, the expulsion type is to be preferred for the reason that its voltage does collapse and thereby aids the functioning of the capacitors and arresters at the machine.

Conclusion

This paper describes the operating characteristics of the two types of lightning arresters and discusses their advantages and disadvantages. A generalized comparison is shown by Table II. If there were conclusive evidence as to the superiority of one type over another, only one type would be in demand and only one type manufactured. Manufacturers who build both do so, because they believe that superiority of one type over the other cannot be demonstrated clearly and that operating engineers will insist that both be available. It is the authors' opinion that both devices serve the purpose for which lightning arresters are intended. There are certain advantages that can be cited for either one. Probably the selection of one or the other is influenced largely by the weight given by the user to those points in which the expulsion and valve arresters for distribution service differ.

Reference

1. Lightning Protection for Rotating Machines, G. D. McCann, E. Beck, L. A. Finzi. AIEE Transactions, volume 63, 1944, pages 319–33.

Resistance and Capacitance Relations Between Short Cylindrical Conductors

F. L. ReQUA
MEMBER AIEE

THE CONVENTIONAL FORMULA for computing capacitance or conductance between parallel cylindrical conductors is derived on the assumption that the electrostatic or current flux between conductor surfaces is confined to paths lying in planes perpendicular to the axes of the conductors.

Actually this condition obtains only at the mid-point between the ends of the conductors. At all other points along the length the lines of flux curve outwardly toward the ends. However, for conductors of length which is very great compared to the distance of separation the flux paths are nearly planar except near the ends. Hence the conventional formula, which indicates direct proportionality between capacitance or conductance and length of the conductors, gives values which approach more and more closely to the true value as the length of the conductors increases.

For relatively short conductors however the effect just mentioned becomes of increasing importance. The true capacitance or conductance is not even approximately proportional to length of conductors and the values given by the conventional formula are no longer satisfactory.

In this paper formulas are developed in which the end effect is taken into account. This leads to an indicated integration which can be closely approximated by the summation of a small number of terms but is inconvenient for engineering computation. It is found that the func-

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tion to be integrated may be approximated by a parabolic function and by this empirical substitution simplified formulas are derived which give results of satisfactory precision for the requirements of engineering design and may be expressed in simple functional form. Tabulated values of this function are given in the paper.

Experimentally determined values obtained from tests on a large three-phase water rheostat at Bonneville are compared with the same quantities computed by the formulas derived in this paper, and the agreement is found to be satisfactory.

Relationship Between Formulas for Capacitance and Conductance

The electrical capacitance C between any two conductors, spatially related in a specified manner and immersed in a dielectric medium of permittivity p, bears a simple relation to the conductance G between the same conductors immersed in a medium of conductivity γ. It is

$$C/p \propto G/\gamma \tag{1}$$

The constant of proportionality will depend upon the system of units adopted. In this paper all derivations are based upon the meter-kilogram-second system, modified so that the unit of length is inches instead of meters. Hereby the unit of capacitance is the farad, of conductance the mho, of resistance R the ohm, of conductivity the mho per inch cube, of resistivity ρ the ohm per inch cube and

$$C/p = G/4\pi\gamma = \rho/4\pi R \tag{2}$$

The absolute permittivity p in equation 2 is the permittivity p_0 of free space multiplied by the dielectric constant k of the medium. In the system of units used herein p_0 has the value 2.8262×10^{-13}.

All formulas in this paper are derived initially for the capacitance between parallel cylindrical conductors of equal diameter. Corresponding formulas for resistance between the conductors then are obtained by use of the relations 2.

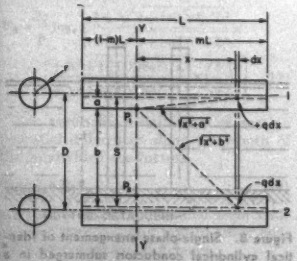

Figure 1. Space relation between elements of equivalent linear charges and surface potential points on two parallel cylindrical conductors

Derivation of Conventional Formula for Capacitance

The conventional formula for capacitance between two parallel cylindrical conductors 1 and 2 of length L, radius r, and distance D between centers, is derived on the assumption that L is so large compared to D that, for a given difference of potential between the conductors, the charge per unit of axial length may be considered to be the same at all points along the length of each conductor.

The surface charge per unit length so transferred can be shown to be the electrostatic equivalent, for points lying outside the conductor surfaces, of the same charge per unit length concentrated along a line inside each conductor in the plane of and parallel to the axes of the two conductors.

When L is very large compared to D the distance S between these two lines of charge is related to D and r by the expression:[1]

$$S = \sqrt{D^2 - 4r^2} \tag{3}$$

The shortest distance a from the line of charge inside conductor 1 to the surface of conductor 1 is readily deduced from equation 3 to be

$$a = \frac{\sqrt{D^2 - 4r^2} - (D - 2r)}{2} \tag{4}$$

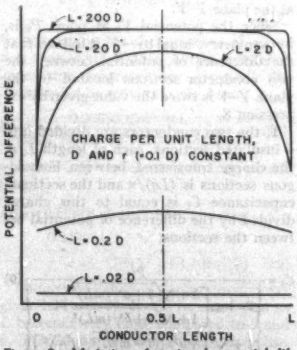

Figure 2. Variation of sectional potential difference with length along parallel cylindrical conductors with uniform linear charge

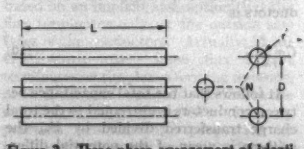

Figure 3. Three-phase arrangement of identical cylindrical conductors, equilaterally spaced in a homogeneous medium of infinite extent

Use formula 20 for capacitance
Use formula 23 for resistance

Similarly, the shortest distance b from the line of charge inside conductor 2 to the surface of conductor 1 is

$$b = \frac{\sqrt{D^2 - 4r^2} + (D - 2r)}{2} \tag{5}$$

From equations 4 and 5 it follows that

$$\frac{b}{a} = \frac{D + \sqrt{D^2 - 4r^2}}{2r} \tag{6}$$

When L is very small compared to both D and r, the relations 3, 4, and 5 are shown in the appendix to change to

$$S = D - \frac{2r^2}{D^2} \tag{3'}$$

$$a = \frac{D^2 - r^2}{D^2} \cdot r \tag{4'}$$

$$b = D - \frac{D^2 + r^2}{D^2} \cdot r \tag{5'}$$

If a linear charge of $+q$ per unit length is assumed within one conductor and $-q$ per unit length within the other, the potential at a point on the surface of each conductor midway between the ends can be computed. The magnitude of the total charge transferred, qL, divided by the computed difference of potential between the mid-points of the two conductors gives the familiar formula[2] for capacitance:

$$C = \frac{0.30685 \times 10^{-13} kL}{\log_{10}\left(\frac{b}{a}\right)} = \frac{0.30685 \times 10^{-13} kL}{\log_{10}\left(\frac{D + \sqrt{D^2 - 4r^2}}{2r}\right)} \tag{7}$$

and thence its approximate equivalent,

$$C = \frac{0.30685 \times 10^{-13} kL}{\log_{10}\left(\frac{D}{r} - \frac{r}{D}\right)} \tag{7'}$$

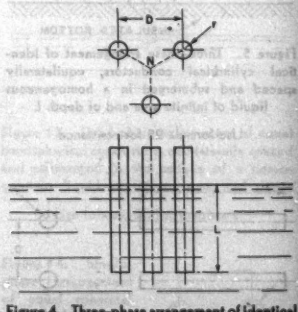

Figure 4. Three-phase arrangement of identical cylindrical conductors, equilaterally spaced and submerged in the surface of a homogeneous liquid of infinite area and depth

Use formula 23 for resistance

The approximate values obtained by use of formula 7′ differ by less than one eighth of one per cent from those of formula 7 for all cases where r does not exceed 20 per cent of D.

Formulas 7 and 7′ and corresponding expressions for resistance derived therefrom are applicable when the flux between conductors follows planes perpendicular to the conductor axes. This condition obtains

1. Approximately, when the length L of the conductors is very great compared to the distance of separation D.

2. Exactly, in the case of electric-current flow, when the conducting liquid of finite depth L is confined in a tank of infinite area with an insulated floor and the conductors are immersed vertically to the full depth of the liquid.

Derivation of More General Formula for Capacitance

Figure 1 represents two parallel tubular conductors of length L and radius r separated by a distance D between axes. It is postulated that each conductor is subdivided into a very large number of short tubular sections formed by cutting through the original conductors with a corresponding number of insulating planes of negligible thickness, each normal to the axes of the conductors. Hereby the necessity of assuming the same potential at all points along the length of the conductor is eliminated.

It is assumed that a charge of q per unit length has been transferred from conductor 2 to conductor 1 and that the resulting deficit and surplus, respectively, of charge are located along two symmetrically disposed lines inside the conductors, separated by the distance S.

If the point P_1 is located at a distance mL from one end of the conductor, where m is a numeric equal to or less than unity, then the potential V_1 at this point is

$$V_1=\frac{q}{p}\left[\int_0^{mL}\frac{dx}{\sqrt{x^2+a^2}}+\int_0^{(1-m)L}\frac{dx}{\sqrt{x^2+a^2}}-\int_0^{mL}\frac{dx}{\sqrt{x^2+b^2}}-\int_0^{(1-m)L}\frac{dx}{\sqrt{x^2+b^2}}\right]$$

$$=\frac{q}{p}\log_e\left[\frac{1+\sqrt{1+a^2/(mL)^2}}{1+\sqrt{1+b^2/(mL)^2}}\times\frac{1+\sqrt{1+a^2/[(1-m)L]^2}}{1+\sqrt{1+b^2/[(1-m)L]^2}}\times\left(\frac{b}{a}\right)^2\right] \quad (8)$$

This is also the potential at all other points on the periphery of the short cylindrical section of conductor 1 located at the plane Y–Y.

Since the potential V_2 at point P_2 is, by symmetry, equal to $-V_1$ it follows that the difference of potential between the two conductor sections located by the plane Y–Y is twice the value given by expression 8.

If the two conductors are divided into n insulated sections, each of length L/n, the charge transferred between homologous sections is $(Lq)/n$ and the sectional capacitance C_t is equal to this charge divided by the difference of potential between the sections,

$$C_t=\frac{pL}{\left\{2n\log_e\left[\frac{1+\sqrt{1+a^2/(mL)^2}}{1+\sqrt{1+b^2/(mL)^2}}\times\frac{1+\sqrt{1+a^2/[(1-m)L]^2}}{1+\sqrt{1+b^2/[(1-m)L]^2}}\times\left(\frac{b}{a}\right)^2\right]\right\}} \quad (9)$$

and the total capacitance between conductors is

$$C=\sum_{t=1}^{n}C_t \quad (10)$$

It follows that the total capacitance between conductors is also equal to the total charge transferred divided by V_m, the arithmetic mean of the potential differences between all pairs of homologous sections. If we refer to Figure 2, which shows sectional difference of potential along the length of pairs of conductors of given r and D but differing length L, it will be noted that for relatively long conductors the mean sectional difference of potential is very nearly the same as the difference of potential at the mid-point. However for shorter conductors this is not true.

A satisfactory approximation for engineering purposes to the mean difference of potential can be obtained by computing the difference of potential at the mid-point of the sectionalized conductor and at two points near to and equidistant from the ends, passing a parabolic curve through these three points and computing the mean difference of potential therefrom. It is found that, if the two end points arbitrarily are taken at nine tenths of the distance from mid-point to end, the approximate value will not differ by more than one half of one per cent from that obtained by subdividing the conductors into 20 sections and using equation 8 as the basis for computation.

The potential at the mid-point and that near either end of one of the sub-

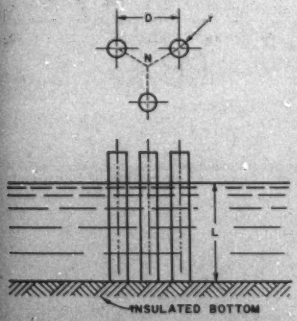

Figure 5. Three-phase arrangement of identical cylindrical conductors, equilaterally spaced and submerged in a homogeneous liquid of infinite area and of depth L

Use formula 25 for resistance

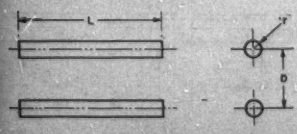

Figure 6. Single-phase arrangement of identical cylindrical conductors in a homogeneous medium of infinite extent

Use formula 18 for capacitance
Use formula 24 for resistance

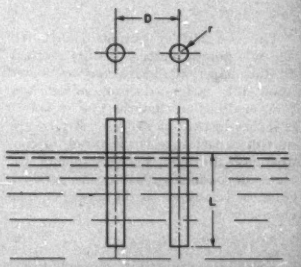

Figure 7. Single-phase arrangement of identical cylindrical conductors submerged in the surface of a homogeneous liquid of infinite area and depth

Use formula 24 for resistance

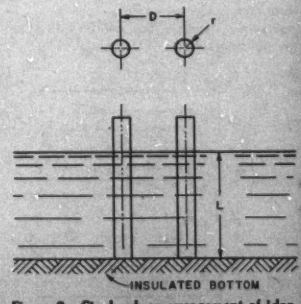

Figure 8. Single-phase arrangement of identical cylindrical conductors submerged in a homogeneous liquid of infinite area and of depth L

Use formula 26 for resistance

Figure 9. Single-phase arrangement of a cylindrical and a plane conductor in a homogeneous medium of infinite extent

Use formula 20 for capacitance
Use formula 23 for resistance

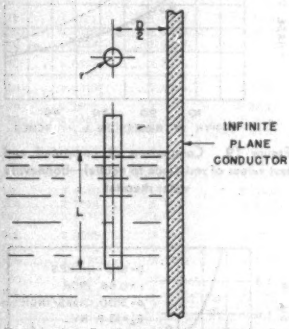

Figure 10. Single-phase arrangement of a cylindrical and a plane conductor submerged in the surface of a homogeneous liquid of infinite area and depth

Use formula 23 for resistance

divided conductors can be determined from equation 8, taking $m = 0.5$ and $m = 0.05$ in turn. The values so obtained, multiplied by two, will give the difference of potential between homologous sections at each of these two locations. If we call the difference of potential at the midpoint V_C and that near the ends V_E,

$$V_C = \frac{4q}{\rho} \log_e \left[\frac{1+\sqrt{1+(4a^2)/L^2}}{1+\sqrt{1+(4b^2)/L^2}} \times \frac{b}{a} \right] \quad (11)$$

$$V_E = \frac{2q}{\rho} \log_e \left[\frac{1+\sqrt{1+(400a^2)/L^2}}{1+\sqrt{1+(400b^2)/L^2}} \times \frac{1+\sqrt{1+(1.108a^2)/L^2}}{1+\sqrt{1+(1.108b^2)/L^2}} \times \left(\frac{b}{a}\right)^2 \right] \quad (12)$$

For parabolic distribution of section potential differences along the length of the subdivided conductors,

$$V_z = A + Bz^2 \quad (13)$$

where z is distance measured from midpoint of the conductor toward either end. The mean potential difference,

$$V_M = \frac{\int_0^{0.5L} V_z dz}{0.5L} = A + \frac{BL^2}{12} \quad (14)$$

If we evaluate the constants A and B from $V_z = V_C$ at $z = 0$ and $V_z = V_E$ at $z = 0.45L$ and substitute into equation 14,

$$V_M = \frac{143 V_C + 100 V_E}{243} \quad (15)$$

If we insert the values of V_C and V_E from equations 11 and 12 into equation 15, the expression for the capacitance between two cylindrical conductors becomes

$$C = \frac{243\rho L}{\left\{ 572 \log_e \left[\frac{1+\sqrt{1+4a^2/L^2}}{1+\sqrt{1+4b^2/L^2}} \times \frac{b}{a} \right] + 200 \log_e \left[\frac{1+\sqrt{1+400a^2/L^2}}{1+\sqrt{1+400b^2/L^2}} \times \frac{1+\sqrt{1+1.108a^2/L^2}}{1+\sqrt{1+1.108b^2/L^2}} \times \left(\frac{b}{a}\right)^2 \right] \right\}} \quad (16)$$

If we replace ρ by its value $2.8262 \times 10^{-12} k$ and convert the logarithms to base ten,

$$C = \frac{0.52142 \times 10^{-12} kL}{\left\{ \log_{10} \left[\frac{1+\sqrt{1+4a^2/L^2}}{1+\sqrt{1+4b^2/L^2}} \times \frac{b}{a} \right] + 0.34965 \log_{10} \left[\frac{1+\sqrt{1+400a^2/L^2}}{1+\sqrt{1+400b^2/L^2}} \times \frac{1+\sqrt{1+1.108a^2/L^2}}{1+\sqrt{1+1.108b^2/L^2}} \times \left(\frac{b}{a}\right)^2 \right] \right\}} \quad (17)$$

By expressing the denominator of equation 17 in terms of sums and differences of logarithms, appropriately grouped, the formula can be written in the form:

$$C = \frac{0.30685 \times 10^{-12} kL}{\log_{10}(b/a) - [F(b/L) - F(a/L)]} \quad (18)$$

where F (—) represents a function such that

$$F(u) = 0.58848 \left[\log_{10}(1+\sqrt{1+4u^2}) + 0.34965 \left\{ (1+\sqrt{1+400u^2}) \times (1+\sqrt{1+1.108u^2}) \right\} \right] \quad (19)$$

Numerical values of the function 19 are given in Table I. It will be noted that as L becomes very large compared to a and b, $F(b/L)$ approaches $F(a/L)$ in value, and thus formula 18 approaches the conventional formula 7 as a limit.

All of the foregoing derivations are based on an implicit assumption that the flux terminates only on the outside surfaces of the conductors. Actually, in the electrostatic case, some flux always terminates on the planes forming the ends, or on the interior surfaces adjacent to the ends if the conductor is tubular. In many practical problems the proportion so terminating is small enough so that it may be neglected without introducing appreciable error. In any event the capacitance given by the formulas will be less than the true value in the ratio of peripheral to total flux.

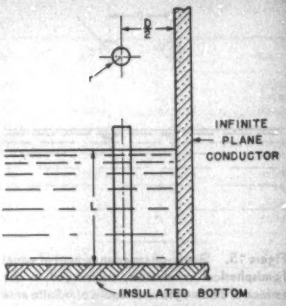

Figure 11. Single-phase arrangement of a cylindrical and a plane conductor submerged in a homogeneous liquid of infinite area and of depth L

Use formula 25 for resistance

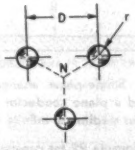

Figure 12. Three-phase arrangement of equal spherical conductors, equilaterally spaced in a homogeneous medium of infinite extent

Use formula 22 for capacitance
Use formula 27 for resistance

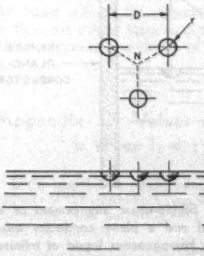

Figure 13. Three-phase arrangement of equal hemispherical conductors, equilaterally spaced and submerged in the surface of a homogeneous liquid of infinite area and depth

Use formula 28 for resistance

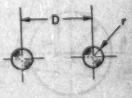

Figure 14. Single-phase arrangement of equal spherical conductors in a homogeneous medium of infinite extent

Use formula 21 for capacitance
Use formula 28 for resistance

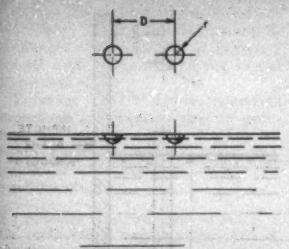

Figure 15. Single-phase arrangement of equal hemispherical conductors, submerged in the surface of a homogeneous liquid of infinite area and depth

Use formula 29 for resistance

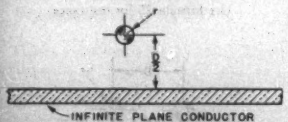

Figure 16. Single-phase arrangement of a spherical and a plane conductor in a homogeneous medium of infinite extent

Use formula 22 for capacitance
Use formula 27 for resistance

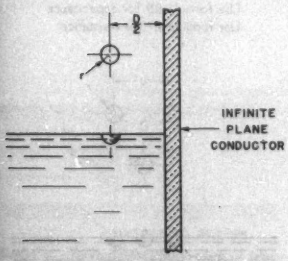

Figure 17. Single-phase arrangement of a hemispherical and a plane conductor submerged in a homogeneous liquid of infinite area and depth

Use formula 28 for resistance

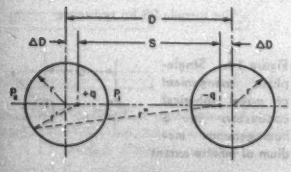

Figure 18. Position of equivalent internal charge in short cylindrical conductors

In the resistance case, it is possible for the plane ends of the conductors to be of insulating material, and in this event the fact accords with the assumption. Otherwise, the same comment applies as for the electrostatic case, except that the error is in the opposite sense so that the resistance given by the formulas will be greater than the true value in the ratio of total to peripheral flux.

Formulas for Capacitance and Resistance

In the following formulas, all linear dimensions are in inches, k is the dielectric constant of the medium (unity for air), and ρ is the resistivity of the medium in ohms per inch cube. C, the capacitance in farads and R, the resistance in ohms, are from line to line for single-phase circuits and from line to neutral for three-phase circuits. F (—) is the function of which tabulated values are given in Table I.

In addition to formulas based on the derivations given in this paper, approximation formulas for capacitance and resistance between spheres are included for convenience. The accuracy of these latter increases as D/r increases, capacitance formulas 21 and 22 giving values lower than actual, resistance formulas 27, 28, and 29 giving values higher than actual, by the percentages indicated in Table II.[3]

For $L \gg D$,

$$a = \frac{\sqrt{D^2-4r^2}}{2} - \frac{D-2r}{2} \tag{4}$$

$$b = \frac{\sqrt{D^2-4r^2}}{2} + \frac{D-2r}{2} \tag{5}$$

$$\frac{b}{a} = \frac{D+\sqrt{D^2-4r^2}}{2r} \tag{6}$$

For $L \ll D$,

$$a = \left[1-\left(\frac{r}{D}\right)^2\right] \times r \tag{4'}$$

$$b = D - \left[1+\left(\frac{r}{D}\right)^2\right] \times r \tag{5'}$$

Capacitance Formulas

Figure 6:

$$C = \frac{0.3068\, kL \times 10^{-12}}{\log_{10}(b/a) - [F(b/L) - F(a/L)]} \tag{18}$$

Figures 3, 9:

$$C = \frac{0.6137\, kL \times 10^{-12}}{\log_{10}(b/a) - [F(b/L) - F(a/L)]} \tag{20}$$

Figure 14:

$$C = \frac{1.411\, kDr \times 10^{-12}}{D-r} \tag{21}$$

Figures 12, 16:

$$C = \frac{2.822\, kDr \times 10^{-12}}{D-r} \tag{22}$$

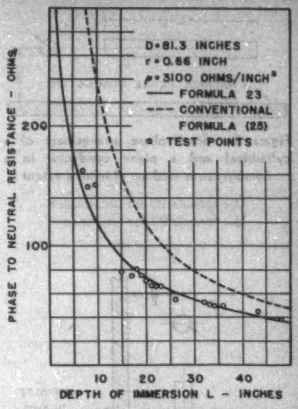

Figure 19. Comparison of computed and test values of resistance to neutral—Bonneville water rheostat

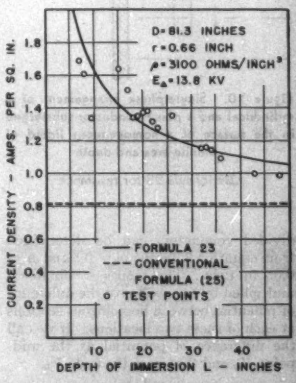

Figure 20. Comparison of computed and test values of electrode-surface current density—Bonneville water rheostat

Resistance Formulas

Figures 3, 4, 9, 10:

$$R = 0.3665 \frac{\log_{10}(b/a) - [F(b/L) - F(a/L)]}{L} \rho \tag{23}$$

Figures 6, 7:

$$R = 0.7330 \frac{\log_{10}(b/a) - [F(b/L) - F(a/L)]}{L} \rho \tag{24}$$

Figures 5, 11:

$$R = 0.3665 \frac{\log_{10}(b/a)}{L} \rho \tag{25}$$

Table I. Values of the Function $F(u)$

u	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.0	0.3010	0.3468	0.3957	0.4366	0.4733	0.5075	0.5397	0.5701	0.5990	0.6264
1.0	0.6524	0.6779	0.7019	0.7246	0.7461	0.7666	0.7861	0.8049	0.8229	0.8402
2.0	0.8569	0.8730	0.8886	0.9037	0.9184	0.9326	0.9464	0.9599	0.9730	0.9858
3.0	0.9983	1.0100	1.0214	1.0327	1.0437	1.0545	1.0651	1.0756	1.0857	1.0957
4.0	1.1055	1.1151	1.1244	1.1335	1.1425	1.1512	1.1597	1.1680	1.1761	1.1840
5.0	1.1917	1.1994	1.2069	1.2144	1.2217	1.2290	1.2361	1.2432	1.2501	1.2570
6.0	1.2637	1.2703	1.2769	1.2833	1.2896	1.2959	1.3020	1.3080	1.3140	1.3198
7.0	1.3255	1.3312	1.3368	1.3423	1.3478	1.3533	1.3587	1.3640	1.3692	1.3744
8.0	1.3796	1.3847	1.3897	1.3947	1.3996	1.4044	1.4092	1.4140	1.4186	1.4232
9.0	1.4278	1.4323	1.4368	1.4413	1.4457	1.4501	1.4544	1.4586	1.4628	1.4670

u	0	1	2	3	4	5	6	7	8	9
10	1.4711	1.5103	1.5463	1.5796	1.6106	1.6396	1.6668	1.6924	1.7166	1.7395
20	1.7613	1.7820	1.8019	1.8208	1.8369	1.8563	1.8730	1.8890	1.9045	1.9194
30	1.9338	1.9473	1.9606	1.9736	1.9863	1.9988	2.0110	2.0229	2.0345	2.0459
40	2.0569	2.0678	2.0783	2.0886	2.0986	2.1083	2.1177	2.1269	2.1358	2.1443
50	2.1527	2.1611	2.1694	2.1775	2.1856	2.1935	2.2012	2.2089	2.2165	2.2239
60	2.2312	2.2384	2.2454	2.2524	2.2592	2.2659	2.2725	2.2790	2.2853	2.2915
70	2.2976	2.3037	2.3097	2.3156	2.3214	2.3272	2.3330	2.3386	2.3442	2.3498
80	2.3552	2.3606	2.3659	2.3712	2.3764	2.3815	2.3865	2.3915	2.3965	2.4013
90	2.4061	2.4109	2.4156	2.4203	2.4250	2.4293	2.4340	2.4385	2.4429	2.4473

u	0	10	20	30	40	50	60	70	80	90
100	2.4516	2.4926	2.5302	2.5648	2.5969	2.6268	2.6548	2.6811	2.7059	2.7294
200	2.7516	2.7728	2.7930	2.8123	2.8307	2.8485	2.8655	2.8818	2.8975	2.9128
300	2.9273	2.9410	2.9545	2.9676	2.9805	2.9931	3.0055	3.0175	3.0293	3.0408
400	3.0520	3.0630	3.0736	3.0840	3.0941	3.1039	3.1134	3.1227	3.1317	3.1404
500	3.1489	3.1573	3.1656	3.1738	3.1819	3.1899	3.1977	3.2054	3.2130	3.2205
600	3.2279	3.2351	3.2422	3.2492	3.2561	3.2629	3.2695	3.2760	3.2824	3.2887
700	3.2948	3.3009	3.3069	3.3129	3.3188	3.3247	3.3304	3.3361	3.3418	3.3473
800	3.3528	3.3582	3.3636	3.3689	3.3741	3.3792	3.3843	3.3893	3.3942	3.3991
900	3.4039	3.4087	3.4135	3.4182	3.4228	3.4274	3.4320	3.4365	3.4409	3.4453

Figure 8:

$$R = 0.7330 \frac{\log_{10}(b/a)}{L} \rho \qquad (26)$$

Figures 12, 16:

$$R = 0.7970 \frac{D-r}{Dr} \rho \qquad (27)$$

Figures 13, 14, 17:

$$R = 0.1594 \frac{D-r}{Dr} \rho \qquad (28)$$

Figure 15:

$$R = 0.3188 \frac{D-r}{Dr} \rho \qquad (29)$$

Comparison Between Test Values and Those Computed by Formula

At the time acceptance tests were to be made on the generators at Bonneville power plant the need arose for a conveniently adjustable artificial load. Accordingly, a preliminary experimental water rheostat was constructed and tested by R. L. Earnheart of the Corps of Engineers, United States Army.[4] Mr. Earnheart is now on foreign duty with the Army and it is through the courtesy of F. M. Lewis, senior engineer, War Department, Portland, Oregon, District, that data from the original field notes have been made available to the author.

The tests were made on a three-phase rheostat immersed in the water of the tailrace. It consisted of three one-inch standard iron pipes parallel to one another and equilaterally spaced 81.3 inches between centers, Figure 4. Readings of current were taken at recorded line-to-line potentials between 12 and 14 kv and at immersion depths varying from 7 to 48 inches. The depth of tailrace water was 50 to 56 feet during the tests.

Table II. Error in Formulas 21, 22, 27, 28, and 29

$\frac{D}{r}$	Per-Cent Error
2.1	20.8
2.2	14.8
2.5	6.25
3.0	2.28
3.5	1.14
4	0.60
5	0.24
6	0.17

In the reference article it is stated that the resistivity ρ of Columbia River water is 3,620 ohms per inch cube at 45 degrees Fahrenheit and 2,200 ohms per inch cube at 80 degrees Fahrenheit. Water temperature during tests, which would be expected to vary somewhat with load, was not given. An intermediate value of 3,100 ohms per inch cube, which seems to approximate the data best, therefore has been used for computations.

Computed values are compared graphically with test values in Figures 19 and 20. Figure 20, in particular, emphasizes the basic difference between the conventional formula 25 and that developed in this paper, 23, for relatively small depth of immersion. The former indicates no change in electrode-surface current density with depth of immersion; the latter reflects the observation made in this and other[5] tests that the current density increases as depth of immersion decreases.

Appendix I. Values of a and b When $L \ll r$

If the length L is small, compared to the radius r of the conductors, and if in addition the radius does not exceed 0.1 D, then at point 1, Figure 18,

$$r_1' = r - \Delta D$$
$$r_1'' = D - \Delta D - r$$

and V_1 is proportional to

$$\frac{1}{r_1'} - \frac{1}{r_1''} = \frac{1}{r-\Delta D} - \frac{1}{D-\Delta D-r} =$$

$$\frac{1}{r}\left(1+\frac{\Delta D}{r}\right) - \frac{1}{D}\left(1+\frac{\Delta D}{D}+\frac{r}{D}\right) =$$

$$\frac{1}{r} + \frac{\Delta D}{r^2} - \frac{1}{D} - \frac{\Delta D}{D^2} - \frac{r}{D^2}$$

Similarly, at point 2,

$$r_2' = r + \Delta D$$
$$r_2'' = D - \Delta D + r$$

Automatic Temperature Control for Aircraft

R. A. GUND
ASSOCIATE AIEE

AUTOMATIC temperature control for aircraft long has been neglected, and it is only during the war that adequate attention has been given to this important subject. The increased duties imposed upon flight personnel by the requirements of modern military aircraft, together with the necessity for reducing air drag to the minimum consistent with required cooling, have prompted aircraft designers to give consideration to automatic operation of cowl flaps, oil and coolant flaps, and intercooler doors. Automatic flap operation can be appreciated fully when it is considered that engine cowl flaps fully opened might represent an air drag as high as 40 miles per hour on a 400-mile-per-hour airplane.

A primitive form of automatic temperature control was used initially on oil or coolant and employed the by-pass valve principle. This method directed the oil or coolant through or around the cooling surface in response to its temperature. Serious problems of oil congealing were introduced. As this type of control provides no control of the air through the cooler, the drag on the airplane is dictated by the amount of air required to provide the necessary cooling under the most adverse conditions of heat release, cooling air temperature, air density, and air speed. Much has been done to reduce congealing difficulties, but many authorities believe that fast-acting controls, operating to modulate the cooling air supply, offer the most direct approach to the problem.

Since most cooling flaps or doors are subjected to air loads of considerable magnitude, an electric motor or hydraulic servo mechanism is used as the load actuating device. The operating characteristics of the load actuating device are allied closely to the over-all operation of the system and must be considered as a component part of the system. The control of engine-head, oil or coolant, and carburetor-air temperature requires the same fundamental equipment, and further discussions will be confined to engine-head control as a representative system.

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Types of System

Before any detailed discussion of automatic temperature control is attempted, it is desirable to establish complete understanding of the various types of systems together with a clear appreciation of the limitations and advantages offered by each. The more common classifications are described briefly under the headings by which they are generally known. Only electric types of thermosensitive elements are considered, although it is understood that the same fundamentals apply if the thermosensitive element is

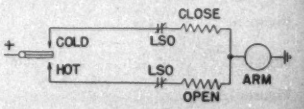

Figure 1. Schematic diagram of on–off system of temperature control

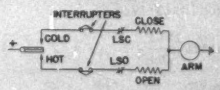

Figure 2a. Schematic diagram of point-modulating system of temperature control showing use of periodic interrupters

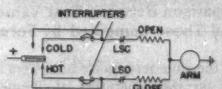

Figure 2b. Schematic diagram of point-modulating system of temperature control showing by-pass principle

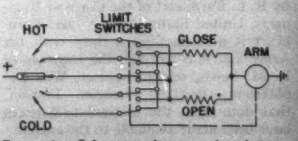

Figure 3. Schematic diagram of multipoint system of temperature control

and V_1 is proportional to

$$\frac{1}{r_1'}-\frac{1}{r_1''}=\frac{1}{r+\Delta D}-\frac{1}{D-\Delta D+r}\approx$$

$$\frac{1}{r}\left(1-\frac{\Delta D}{r}\right)-\frac{1}{D}\left(1+\frac{\Delta D}{D}-\frac{r}{D}\right)\approx$$

$$\frac{1}{r}-\frac{\Delta D}{r^2}-\frac{1}{D}-\frac{\Delta D}{D^2}+\frac{r}{D^2}$$

In order that V_1 shall equal V_2

$$\frac{1}{r}+\frac{\Delta D}{r^2}-\frac{1}{D}-\frac{\Delta D}{D^2}-\frac{r}{D^2}$$

$$=-\frac{1}{r}-\frac{\Delta D}{r^2}-\frac{1}{D}-\frac{\Delta D}{D^2}+\frac{r}{D^2}$$

from which $\Delta D = r^2/D^2$ and

$$S=\frac{D^2-2r^2}{D^2}$$

$$a=\frac{D^2-r^2}{D^2}\times r$$

$$b=D-\frac{D^2+r^2}{D^2}\times r$$

Appendix II. List of Symbols

A = constant, equation 13
B = constant, equation 13
C = capacitance, farads
D = conductor spacing, inches
$F(u)$ = a function of the numeric u (see Table I)
G = conductance, mhos
L = conductor length, inches
R = resistance, ohms
S = hypothetical charge spacing, inches
V = potential, volts
a = shortest distance from hypothetical line of charge to surface of the same conductor, inches
b = shortest distance from hypothetical line of charge to surface of the opposite conductor, inches
k = dielectric constant of the medium
m = distance from a point to the end of the conductor, in terms of L
n = number of hypothetical insulated sections into which the conductor is assumed to be divided
p_0 = permittivity of free space, 2.870×10^{-13} in the dimensional system used in this paper
p = permittivity of the medium, kp_0
q = charge, coulombs
r = radius of conductors, inches
γ = conductivity, mho per inch cube
ρ = resistivity, ohms per inch cube

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4. WATER RHEOSTAT IS TEST LOAD FOR BONNEVILLE, R. L. Earnheart. *Electrical West*, volume 81, number 3, September 1938.

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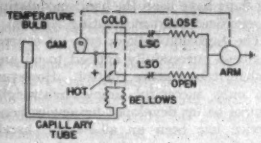


Figure 4a. Schematic diagram of the bulb-and-bellows type of band-modulating temperature-contol system

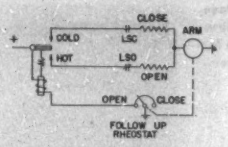


Figure 4b. Schematic diagram of an electric type of band-modulating temperature-control system

used to actuate hydraulic or pneumatic valves instead of electric contacts.

On–Off System

The on–off system is the simplest of all temperature-control methods. It is well exemplified by the conventional household heating system. In this system a thermostat is calibrated to open or close contacts at some predetermined temperature. When the temperature is below this value, circuits are completed to start the heat-generating equipment. When the temperature rises to the calibrated value, the supply of heat is discontinued.

The on–off system is shown schematically in Figure 1. When the engine-head temperature reaches a predetermined value, the hot contact is closed, which energizes the flap motor in the open direction. When the temperature falls to a predetermined value, the cold contact is energized, and the flaps are closed. This system might tend to hold engine-head temperatures within narrow limits, but the resulting duty cycle would be quite impractical from the standpoint of the life of the equipment. Flying characteristics also would be affected violently, as the flaps suddenly would go wide open or completely closed.

Point-Modulating System

In an attempt to overcome the deficiencies of the on–off system, the point-modulating system was developed. This system must have the speed of flap opening or flap closing slow enough to permit stabilization before reaching the limits of travel. Various methods have been employed to reduce the speed of flap operation. One such method is shown in Figure 2a, where interrupters are interposed between the thermostat and the motor to permit opening and closing in a series of increments. This gives the cowl flaps more positions and permits the temperature of the engine to stabilize, which allows the thermostat to assume a neutral position. Modifications of this general idea range from thermal time relays to interrupters operated by centrifugal action from the flap motor. Another modification of this system is that shown in Figure 2b, wherein the interrupter is by-passed when the temperature is at wide variance but becomes operative as the temperature approaches the balance point.

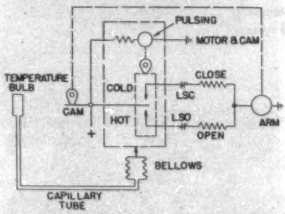


Figure 5. Schematic diagram of the sensitized band-modulating system of temperature control

This system introduces the element of time, and it is almost impossible to balance the time of flap operation with the time constant of the heating or cooling system. For instance the engine-head time constant varies over a wide range with the power output of the engine.

In many industrial applications where only a single variable exists, the point-modulation system has been successfully applied. However, in aircraft work where the cooling air temperature, air density, air speed, and heat release represent the variables, any attempt to fit the time of flap operation to the wide range of conditions encountered becomes an extremely difficult problem.

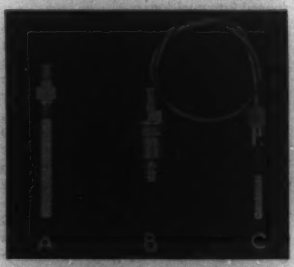


Figure 6. Electric thermosensitive elements

A—Oil or coolant service
B—Carburetor-air service
C—Engine-head service
Respective weights: 0.167 pound, 0.088 pound, 0.093 pound

Multipoint System

In this system the thermostat becomes a multicontact device with each contact representing a definite flap position as shown in Figure 3. As the temperature of the controlled medium varies, the flaps assume corrective positions until a balance is reached where the cooling supply approaches the cooling demand. To be successful this system requires a reasonable number of steps or points on the thermostat. If the thermostat has many points, then a large number of conductors between the thermostat and motor or limit switch assembly are required. If a small number of points are used, continuous hunting may result between the two steps nearest the required flap opening. This type of thermosensitive element is large and bulky and is very difficult to apply.

Band-Modulating System

Band-modulating temperature control may be defined as a control which recalibrates the temperature-sensing element as the flaps assume successive positions. As its name implies, the band-modulating system operates over a temperature range. The temperature range or band width is determined by two factors: system sensitivity, that is, the temperature change required to make the control operate and the number of flap positions required by the airplane's cooling system in order to obtain stable operation. Figure 4a is a typical aircraft control system of this type where the thermosensitive element is the bulb of a bulb-and-bellows assembly, and where the follow-up or

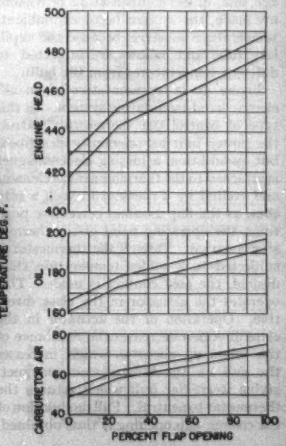
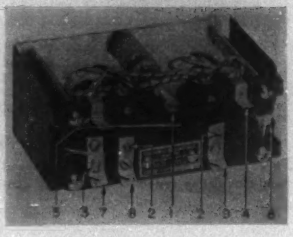


Figure 7. Temperature–resistance curves for engine-head, oil, and carburetor-air thermosensitive elements

Figure 8. Open and enclosed views of the controller for automatic temperature control

Weight, 3.5 pounds

Figure 9 (below). Terminal identification of the polarized relay used in the automatic temperature-control system



recalibrating action is obtained by cam motion in the power unit. In this system one element of the contact mechanism is moved by the pressure in the bellows, while the recalibrating action is obtained through the cam which returns the other element of the contact mechanism to neutral. Many modifications of this system have been employed, differing chiefly in the type of follow-up mechanism used.

One of the difficulties of this system is in the relatively large size and low response rate of the bulb. In order to obtain the degree of sensitivity required, the amount of liquid in the bulb must be relatively large, and, since the ratio of surface to volume is low, the response rate is correspondingly low. In order to overcome this difficulty some systems employ multiple bulbs connected to a common bellows, thus giving a lower ratio of volume to surface. This, of course, takes more space. Another difficulty encountered in this system is the use of a capillary tube. If a long run is necessary, it becomes vulnerable to damage, and, unless compensating provisions are made, the system becomes ambient-temperature sensitive, because the capillary tube and bellows are subjected to different temperatures from the bulb.

Figure 4b is representative of an all-electric band-modulating system. In this type of control the thermostat controls the power unit as previously described, but, in addition, a biasing electromagnet is attached to the thermosensitive element and excited by a rheostat in such a way that, as the flap assumes corrective positions, the operating point of the thermostat is varied. Thus, if the thermostat is subjected to a colder temperature than desired, the cold contact is made. This operates the actuator in the close direction. Operation of the actuator in the close direction decreases the resistance of the follow-up rheostat which increases the pull on the biasing electromagnet, giving it greater pull which returns the thermostat to neutral. Full modulation of the cooling flap opening is thus obtained.

Sensitized Band-Modulating System

In an effort to obtain higher system sensitivity and, therefore, narrower band widths several schemes, all basically alike, have been devised. A mechanical pulse is imposed on the system such that in its neutral position the control almost operates in either direction; a slight change in temperature will cause a small correction to be made in the flap position. Figure 5 represents such a system. A small motor continuously operates a cam, which in turn moves the contacts up and down so that they almost make contact. If the bellows either expands or contracts slightly, a momentary contact is made, and the flap motor is jogged in the proper direction. If a large change should take place, the pulsing action will not break the contact until the flap is almost in position, at which time the flap will be jogged into position.

Very sensitive systems can be made in this manner, but the more sensitive the system becomes the greater the duty cycle of the flap actuator becomes. Also the pulsing motor must be a continuously rated motor with exceptionally long life.

Since the advent of the resistance-bulb temperature indicators, several electronic temperature control systems have been designed. Narrow band widths can be obtained because of the great amplification obtained with electronic tubes. However, an electronic system has a great weight disadvantage because of the extra equipment necessary such as inverters, transformers, and so forth.

An Electric System

The only systems which have had any success in controlling engine-head cooling flaps have been the band-modulating or sensitized-band-modulating systems.

The bulb-and-bellows type of control has been successfully applied to oil and coolant temperature control. However, the only successful simple lightweight control so far developed for engine-head service has been an all-electric band-modulating system which, with the use of different thermosensitive elements, also will control oil carburetor-air, or coolant temperatures.

Components of the System

The system consists of a thermosensitive element, an actuator, which may be either an electric motor or hydraulic servo mechanism, and a follow-up rheostat to recalibrate the system. The necessary cockpit switch and limit switches also must be included.

The thermosensitive element, see Figure 6 for illustrations, consists of a material which has a high negative temperature coefficient of resistance. Figure 7 shows the resistance temperature curves for three types of elements: engine head, oil, and carburetor air. The constants of the circuit are such that the thermosensitive element always has approximately constant wattage input over the systems operating band. This heat input is such that the thermosensitive elements themselves are always at a higher temperature than the body being cooled.

The controller, Figure 8, consists of a very sensitive polarized relay and power relays. The power relays control the operation of the flap motor; they are of conventional design.

The polarized relay works in conjunction with the thermosensitive element and the follow-up rheostat and controls the power relays. The relay, Figure 9, is a flux-balancing relay. It consists of a permanent magnet for polarization, two coils, and a balanced armature. Each

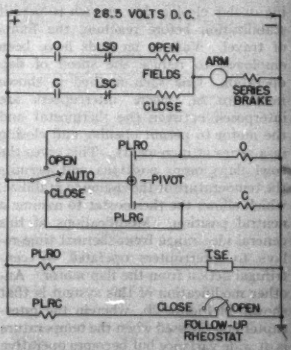


Figure 10. Elementary diagram of an automatic temperature-control circuit

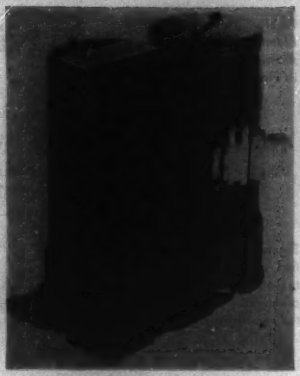
coil has an inside winding, connected in series and to terminals 4 and 5, and an outside winding, connected in series and to terminals 4 and 6. The inside windings have twice as many turns as the outside, but both windings have equal resistance. The armature has a common connection at terminal 7 which may contact either terminal 8 or terminal 9.

Figure 10 is an elementary diagram of the basic circuit. The high-turn windings of the polarized relay are coil *PLRO* and the low-turn windings, coil *PLRC*. In order to balance the relay equal flux must be produced by each coil, therefore, the current through coil *PLRC* must be twice as great as the current through coil *PLRO*. This condition can be met only if the thermosensitive-element (*TSE*) resistance is equal to the resistance of coil *PLRC* plus twice the resistance of the follow-up rheostat.

Inasmuch as the thermosensitive element controls the position of the flap, the excitation of coil *PLRO* always is changed first. When the flap position is changed, it moves the follow-up rheostat until the relay is rebalanced. Figure 11 is a graphical representation of the operation of the polarized relay. Note that it takes a greater change in the flux produced by coil *PLRO* to reverse direction. This is done in order to prevent overshooting or hunting. Coil *PLRO* is energized only 0.8 of a milliwatt greater or less than its balancing excitation in order to operate the relay.

Figures 12 and 13 are typical examples of follow-up units. Figure 12 is a geared actuator with the follow-up unit mounted at the left on the assembly; Fig. 13 is a separately mounted follow-up unit which can be connected by a cable to any part of the flap actuating mechanism which has relatively straight line motion. Both of these units incorporate a rheostat and limit switches. The resistance of the rheostat controls the width of the temperature band as previously described.

Since a given flap change near the flap-closed position produces more cooling effect than the same flap change near the flap-open position, the follow-up rheostat must compensate for this condition by being tapered.



The rheostat in the gear-driven follow-up unit has a tapered winding. The taper is produced by the cam in the separately mounted follow-up unit. Both tapers are shown in Figure 14.

Any conventional actuator, either electric or hydraulic, can be used with this system, so long as it can be stopped quickly.

System Operation

In the diagram, in Figure 10, when the medium to be cooled is at a low temperature, the flaps are closed. The follow-up rheostat then has full resistance in coil *PLRC* circuit. As the medium rises in temperature the temperature-sensing element (*TSE*) decreases in resistance until the excitation of coil *PLRO* is greater than that of coil *PLRC*. This causes contact *PLRO* to close, exciting coil *O*. When coil *O* is energized, it closes contact *O* which energizes the motor in the open direction. As the flaps are opened, the follow-up rheostat decreases in resistance until coil *PLRC* is energized the same amount as coil *PLRO*. This causes contact *PLRO* to open, de-energizing

Figure 13. A separately mounted cam-driven follow-up unit

Weight, 1.32 pounds

Figure 12 (left). Electric actuator with follow-up unit forming a complete unit assembly

Weight of follow-up unit, 1.2 pounds

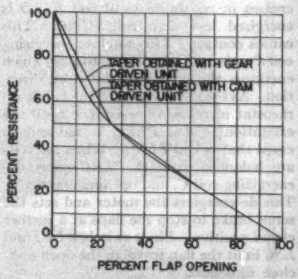


Figure 14. Typical per-cent resistance versus per-cent flap opening curves for follow-up units

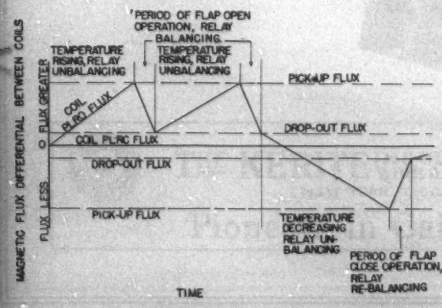


Figure 11. Graphical representation of the polarized-relay operating principle

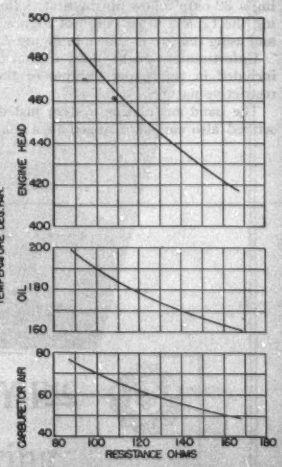


Figure 15. Calculated envelopes of temperature versus per-cent flap opening for engine-head, oil, and carburetor-air service

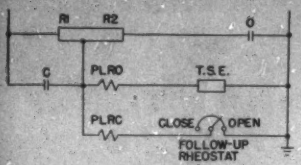


Figure 16 (left). Elementary diagram showing how circuit in Figure 10 can be sensitized

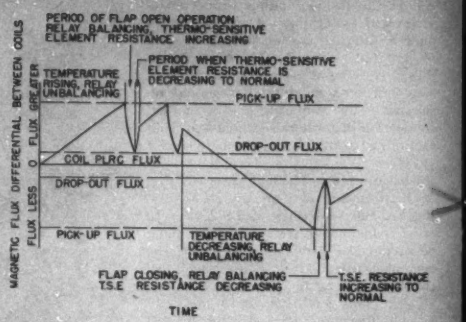


Figure 17. Graphical presentation of the operation of the polarized relay in the sensitized circuit

coil *O*, and opening contact *O*. This de-energizes the motor and sets the series brake, thus stopping the flaps at an open position. If the medium to be cooled is not yet receiving enough cooling air, the same procedure is followed. The flaps will stabilize at a point where the cooling air equals the heat release of the medium.

If the medium drops in temperature, then the temperature-sensing element increases in resistance until coil *PLRO* is energized less than coil *PLRC*. This causes contact *PLRC* to close energizing coil *C* and causing contact *C* to close which energizes the motor in the close direction. As the flaps are closed the follow-up rheostat increases in resistance until the excitation of coil *PLRC* is reduced to equal that of coil *PLRO*. When the coils are balanced, contact *PLRC* opens, de-energizing coil *C*, and opening contact *C*. This de-energizes the motor and sets the series brake to stop the flaps at a further closed position. Limit switches *LSO* and *LSC* limit the flap travel in the open-and-close direction.

Figure 15 shows the various envelopes of temperature versus flap opening for the engine-head, oil, and carburetor-air service. These curves are plotted assuming a 32-ohm follow-up rheostat, following the typical taper curve of Figure 14 and using the curves shown in Figure 7.

Unfortunately flight data cannot be included in this paper because of their restrictive nature.

The band-modulating system just described also can be changed to a sensitized band-modulating system. It must be remembered that the thermosensitive elements dissipate about two watts which causes them to be at a higher temperature than the medium being cooled. If it is possible to introduce less heat to the element when the flaps are opening or more heat to the element when the flaps are closing (preheating and precooling), the system can be sensitized. This is done by varying the voltage across the polarized relay coil circuits as shown in Figure 16.

In the balanced condition the voltage drop across *R*1 is the drop due to the current flowing through the polarized relay coils, the thermosensitive element, and the follow-up rheostat. When the flaps are driven in the open direction, contact *O* closes, which causes an additional voltage drop through *R*1 due to the current drawn through *R*2. Thus the power input to the thermosensitive element is decreased by reducing the voltage across it, which causes the resistance of the element to increase. This causes the polarized relay to rebalance sooner than it normally would.

When the flap is driven in the close direction, contact *C* closes, throwing the sensitive circuit across the line. This increases the power to the thermosensitive element by increasing the voltage across it, which causes the element to decrease in resistance. Again the polarized-relay rebalances sooner than it normally would. Figure 17 presents graphically the operation of the polarized relay under sensitized conditions. Note that a small amount of time is necessary for the relay to build up its flux differential after rebalancing. This prevents relay chatter which is present in every other type of sensitizing scheme so far devised for this system.

Conclusions

Automatic temperature control of cooling flaps increases the performance of the airplane, because it protects against destructive operating temperatures. It insures maximum efficiency and minimum drag by eliminating the human element.

Electric controls are more flexible than mechanical controls and are therefore easier to apply, especially in fighter aircraft where space in certain parts of the air frame is at a premium.

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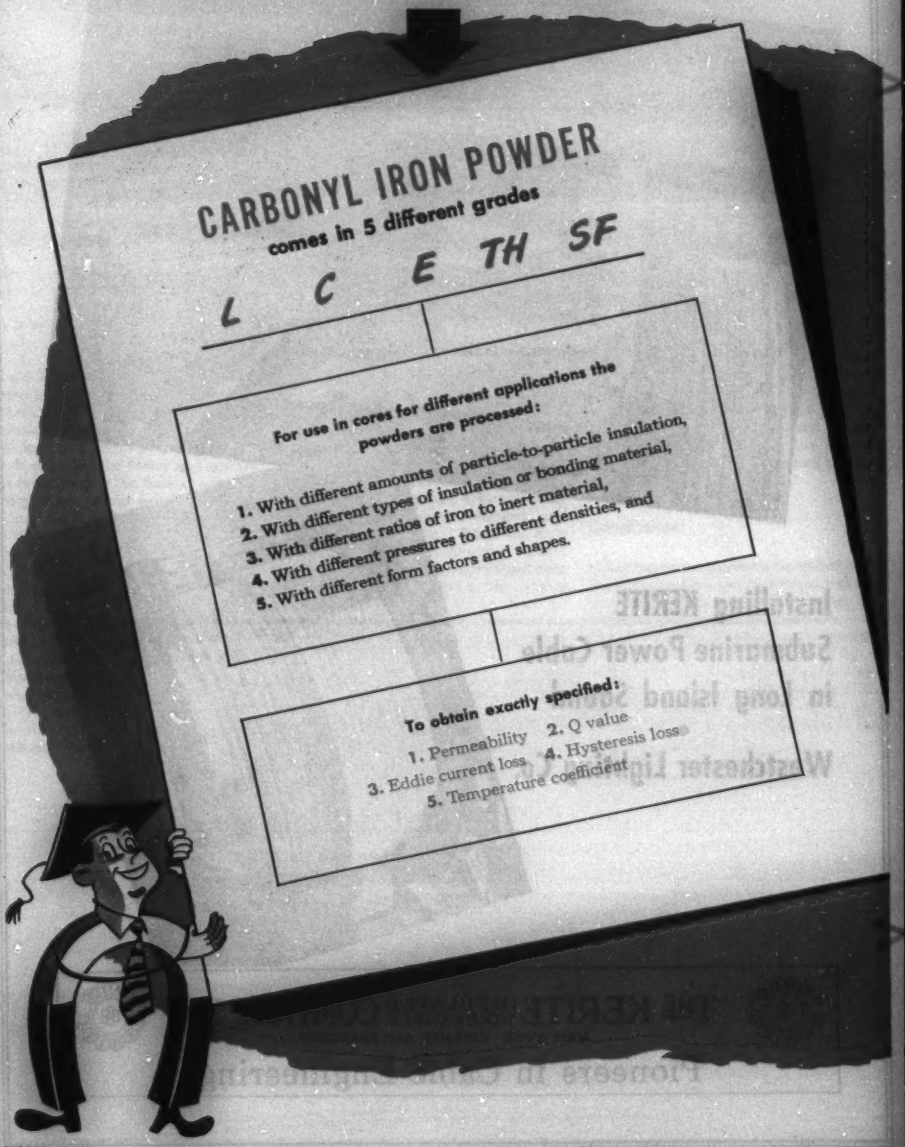
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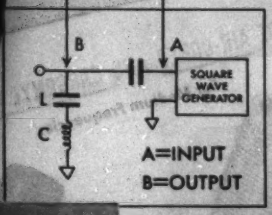
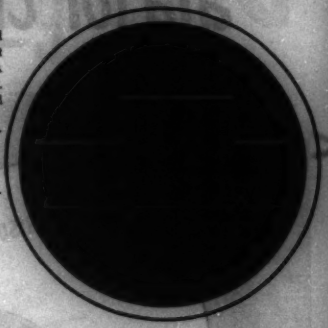
Now it can be told...

The Type 5SP double-beam tube may be used to examine both the input signal to a circuit and the circuit response at the output. A square wave is here applied to an LC circuit. Both input and output signals can be studied simultaneously. Either signal may be expanded for detailed study.

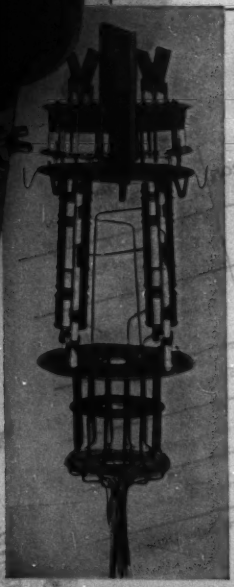




by means of the new **DuMONT**

DOUBLE-BEAM

TYPE 5SP CATHODE-RAY TUBE



Further details on request

New and startling applications are ushered in by this latest DuMont development.

Two complete "guns" in a single 5" envelope converge on one screen for *simultaneous* and superimposed traces. Heretofore such simultaneous comparison of two phenomena could be accomplished either by (1) using two separate tubes or oscillographs placed side by side, or (2) using the electronic switch. Both methods presented limitations either in observation convenience, or in frequency response and inability to use independent time bases.

With the new DuMont Type 5SP double-beam tube there is *complete and independent control* of the X, Y and Z axis functions for each beam. Adequate shielding between "guns" and "plates" minimizes "cross-talk" particularly at high frequencies. Side-wall connections to the deflection plates minimize shunt-input capacitance and lead inductance; also provide better insulation and longer leakage paths. Army-Navy diheptal 12-pin base. Electrode rating similar to Army-Navy preferred Type 5CP1.

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DUMONT *Precision Electronics & Television*

ALLEN B. DUMONT LABORATORIES, INC. PASSAIC, NEW JERSEY • CABLE ADDRESS: WESPEXLIN, NEW YORK

PLUS PROTECTION

AGAINST AMBIENT AND OVERLOAD HEATING WITH DC-993 SILICONE INSULATING VARNISH

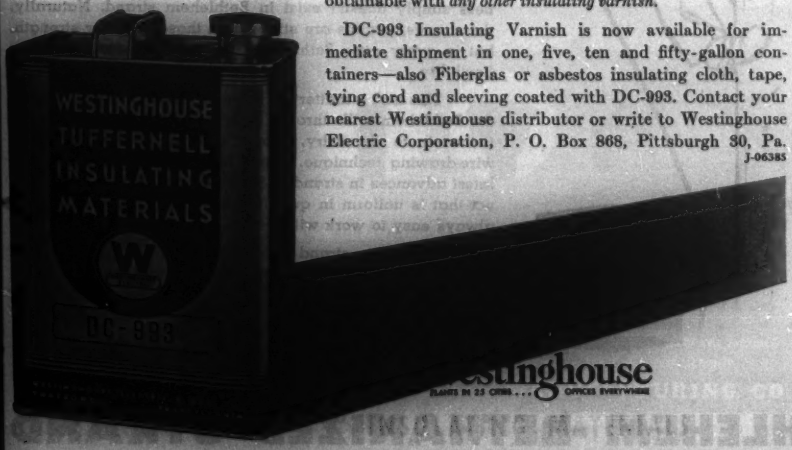
You get 35% *more* heat resisting protection against motor overload failures with DC-993 Silicone Insulating Varnish, than with Class B insulating varnish.

For DC-993 sets a new high in thermal protection. According to AIEE standards No. 1, conventional Class B insulation may come within the limits of 130° C. With DC-993 you have a safe operating temperature of 175° C . . . 35% higher than accepted present-day standards.

DC-993 is a joint development of Dow Corning chemical research and Westinghouse "know-how" in the field of silicones, a new group of semi-inorganic compounds made from sand, brine, coal and oil. It provides an insulating film approaching Fiberglas, mica or asbestos in its ability to resist heat. For example—a generator insulated with DC-993 ran 3000 hours at a temperature of 250°C (482°F) . . . equal to a far longer life at a normal operating temperature than obtainable with *any other insulating varnish.*

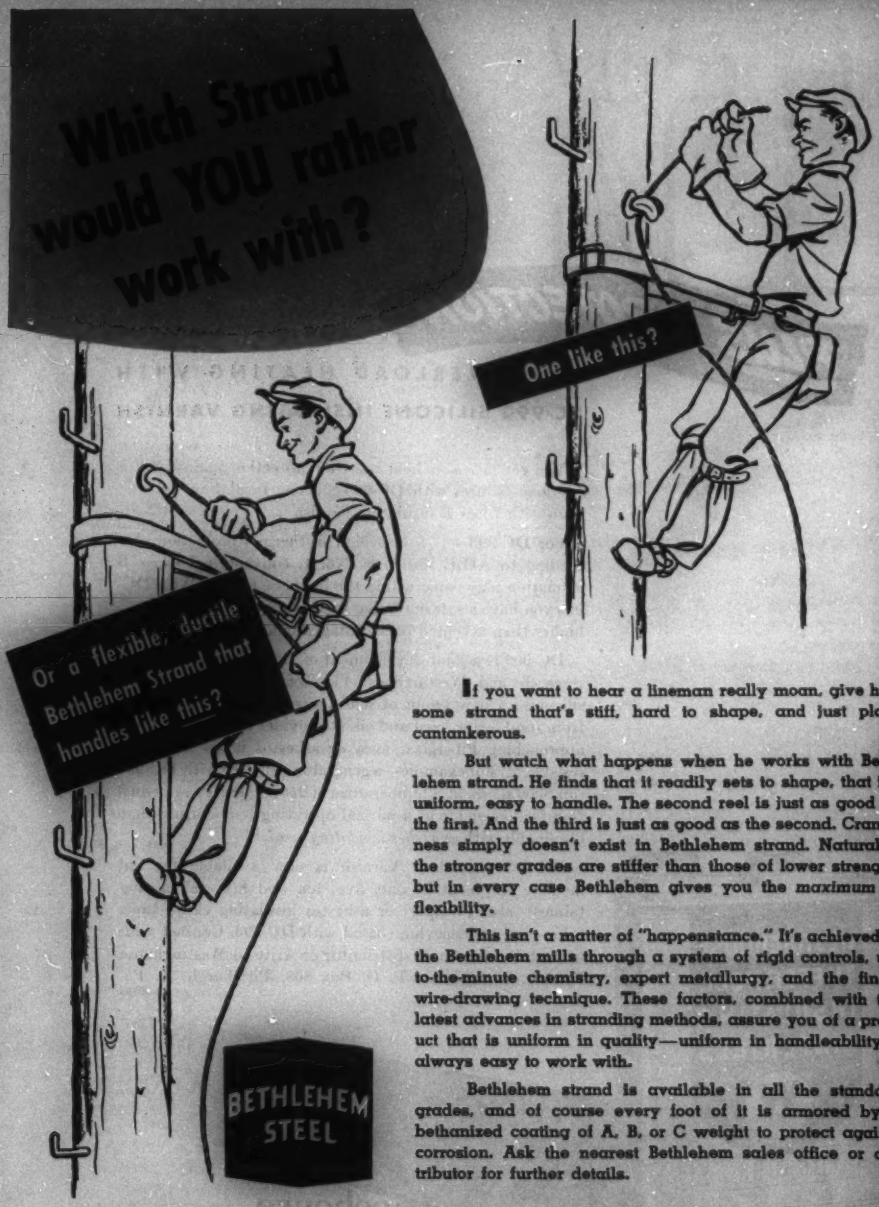
DC-993 Insulating Varnish is now available for immediate shipment in one, five, ten and fifty-gallon containers—also Fiberglas or asbestos insulating cloth, tape, tying cord and sleeving coated with DC-993. Contact your nearest Westinghouse distributor or write to Westinghouse Electric Corporation, P. O. Box 868, Pittsburgh 30, Pa.

J-06385



Westinghouse

PLANTS IN 25 CITIES . . . OFFICES EVERYWHERE


Which Strand would YOU rather work with?
One like this?
Or a flexible, ductile Bethlehem Strand that handles like this?
BETHLEHEM STEEL

If you want to hear a lineman really moan, give him some strand that's stiff, hard to shape, and just plain cantankerous.

But watch what happens when he works with Bethlehem strand. He finds that it readily sets to shape, that it's uniform, easy to handle. The second reel is just as good as the first. And the third is just as good as the second. Crankiness simply doesn't exist in Bethlehem strand. Naturally, the stronger grades are stiffer than those of lower strength, but in every case Bethlehem gives you the *maximum* in flexibility.

This isn't a matter of "happenstance." It's achieved in the Bethlehem mills through a system of rigid controls, up-to-the-minute chemistry, expert metallurgy, and the finest wire-drawing technique. These factors, combined with the latest advances in stranding methods, assure you of a product that is uniform in quality—uniform in handleability—always easy to work with.

Bethlehem strand is available in all the standard grades, and of course every foot of it is armored by a bethanized coating of A, B, or C weight to protect against corrosion. Ask the nearest Bethlehem sales office or distributor for further details.

BETHLEHEM BETHANIZED STRAND

WHEN THE INSULATION GOES—

YOUR TROUBLE STARTS!

WHAT does it mean to *you* when Mrs. Smith's electric iron goes *phht?* If electrical insulation is a part of *your* product, whether it's appliance, radio or electrical equipment, you, like the iron manufacturer, run this *risk*. The risk of insulation failure—of inconveniencing customers, jeopardizing good will, and possibly losing sales.

Since your product's performance may depend on a few cents worth of insulation, be sure to use the best. Assure trouble-free service with BH Fiberglas Sleeving, the *original* non-fraying, non-stiffening, non-burning Fiberglas sleeving. An exclusive BH process combines *permanent* freedom from hardening, cracking or rotting with the many advantages of Fiberglas — including high dielectric and tensile strength, resistance to moisture, oil, grease and most chemicals.

Severest wartime uses prove beyond question the superior qualities of all three BH Fiberglas Sleevings in electrical applications for home and industry. One of them may fit your needs to a "T"—*plus!* Write for free BH samples today and put them to the toughest tests your product can dish out!

3 GREAT BH FIBERGLAS SLEEVINGS—EACH 3 WAYS BETTER!

NON-STIFFENING* NON-FRAYING* NON-BURNING*

BH *EXTRA FLEXIBLE* FIBERGLAS SLEEVING • BH SPECIAL TREATED FIBERGLAS SLEEVING

BEN-HAR COATED FIBERGLAS SLEEVING

*All for usual fabric giving degree above characteristics are contained in these three sleevings. All standard sizes and colors available in standard 24-in. lengths and 500-ft. rolls.

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ALSO SLOW-BURNING IMPREGNATED MAGNETO TUBING • SLOW-BURNING FLEXIBLE VARNISHED TUBING • SATURATED SLEEVING • A.S.T.M. SPECIFICATIONS

BENTLEY, HARRIS MANUFACTURING CO.

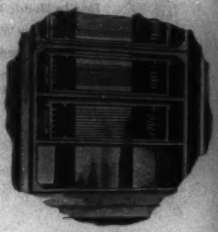
Dept. C Conshohocken, Penna.

he started something that will never stop

25 YEARS AGO a Westinghouse research engineer started something that was destined to have a profound effect upon the lives of all of us . . . and upon generations yet unborn.
That *something* was radio *broadcasting*.

Radio broadcasting was born

on November 2, 1920, when the Presidential Election returns were broadcast from the tiny radio station, KDKA—built by Dr. Frank Conrad at the Westinghouse plant in East Pittsburgh, Pa. It was the first *scheduled radio broadcast* in history . . . the forerunner of a world-wide network that would eventually carry enlightenment and entertainment to the far corners of the earth.



Another "first"

by Westinghouse was the use of radio waves to fuse a mirror-like finish on dull electrolytic tin plate. High-frequency induction heating now helps make *one pound* of war-scarce tin do the work of *three*.

Dielectric death

. . . administered to weevils in grain elevators . . . is another example of the ingenuity of Westinghouse high-frequency engineers. Westinghouse dielectric heating equipment is today speeding the bonding of plywood and curing of plastics and synthetic rubber.

Frequency modulation

was pioneered by Westinghouse scientists as far back as 1920. At that early time they experimented with high frequencies that led the way to the static-free, crystal-clear FM we know today.

Television

has become a reality because of the genius of Westinghouse micro-wave experts, who developed the forerunner of the Iconoscope in 1923 and the Kinescope in 1929. These devices banished forever cumbersome scanning discs.

Research in microwaves

never stops at Westinghouse. Research, begun 20 years ago, resulted in the key electronic tube for the *first* long range Radar equipment. Other secret devices, born of war in the Westinghouse Research Laboratories, will contribute to a better, brighter peacetime world.

Westinghouse
PLANTS IN 25 CITIES OFFICES EVERYWHERE

Tune in: JOHN CHARLES THOMAS—Sunday, 2:30 pm, EWT, NBC • TED MALONE—Monday through Friday, 11:45 am, EWT, American Network

When do you KNOW you have a good suspension insulator?

It's easy to get the answer to the question, "Does this suspension insulator meet established standards?" This answer can come from any well-equipped laboratory.

It's far more difficult to answer this question, however: "How long will this insulator *continue* to meet such standards?" Time is the essence of suspension insulator performance. Insulators can change. Some do.

When new, O-B insulators enjoy no great distinction. New insulators are a highly standardized product. Old insulators, with years of service on their heads, are anything but standardized. Here is the place where differences show up. How can you be sure of the future in buying suspension insulators today?

O-B suspension insulators have repeatedly established official power company records for longest life and lowest depreciation rates in the industry. This is putting it straight! This is the surest answer.

Insulate with O-B and get the same kind of results on your own lines.

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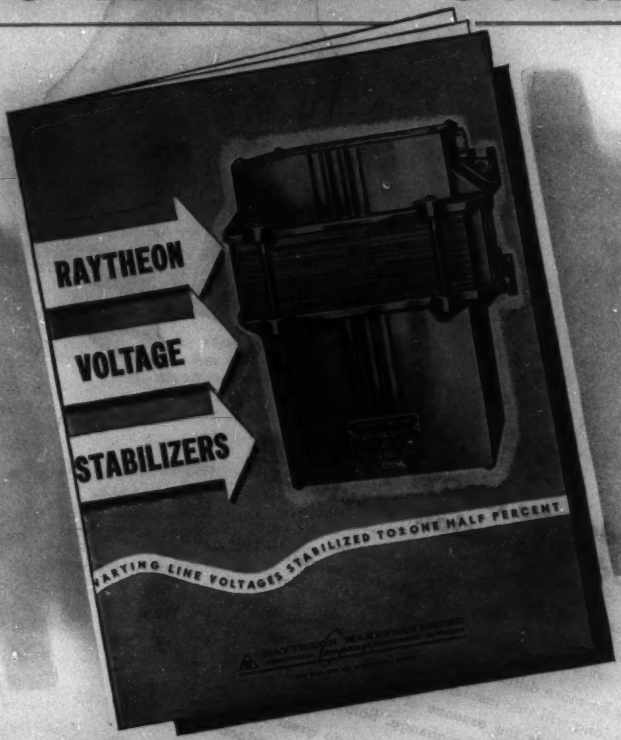
Ohio Brass

MANSFIELD, OHIO

CANADIAN OHIO BRASS CO., LTD., NIAGARA FALLS, ONT.

HERE'S THE FULL STORY



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IN A DETAILED, 8-page bulletin now available, Raytheon Manufacturing Company tells the complete story about the dependable Raytheon Voltage Stabilizers. These trouble-free magnetic-type units ... with no moving parts to get out of order ... stabilize AC from ordinary voltage sources to within plus or minus a half percent, throughout their full rating.

The bulletin includes such useful information as electronic applications, performance features, principles of operation, operating characteristics, graphs, specifications of the three immediately available designs, cased, uncased, and endbell, and a price list.

We urge you to send for your copy promptly. Ask for Bulletin DL48-537, and address your request to Raytheon Manufacturing Company, Electrical Equipment Division, Waltham 54, Mass.

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High dielectric strength — high resistivity—low power factor—wide range of dielectric constants—low losses at all frequencies.

Permanent hermetic seals against gas, oil and water readily made between glass and metal or glass and glass.

Commercial fabrication to the fine tolerances of precision metal working.

Corning's metallizing process produces metal areas of fixed and exact specification, permanently bonded to glass.

AS YOU plan post-war electronic products, give a thought to versatile glass. We really mean glasses, for Corning has, at its fingertips, 25,000 different glass formulae from which to select those especially suited to your electronic applications. Let us show what glass can do for you. We may already have a solution — or Corning Research can find the answer for you. Address Electronic Sales Dept., N-10 Bulb and Tubing Division. Corning Glass Works, Corning, New York.

CORNING *means* Research in Glass

Electronic Glassware

VICOR CORNING PYREX

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That's how they make ONE type of Fiberglas*-Mica combination

Several processors were quick to realize that mica and Fiberglas each have advantages which, when combined, result in an insulation material with unsurpassed characteristics. That is why the combination of thin glass cloth with mica, for ground insulation, was one of the first applications of Fiberglas in the electrical industry.

Types of Fiberglas-Mica Combinations

Fiberglas-Mica combination insulation is available commercially in thicknesses from .004" to .030". The Fiberglas may be applied to one or both facings of the mica, and the thickness of the Fiberglas used may be varied.

For ease in using the material, where minimum space is a factor, Fiberglas may be applied to one surface of the mica, while "fish paper" is applied to the other. In all cases, the strength of the Fiberglas-Mica combination is in excess of any other type of reinforced mica of the same thickness. This is particularly important in the thinnest mica tapes used for conductor or coil insulation. Four mil thick Fiberglas-Mica Tape is nearly three times as strong as the same thickness of mica tape with silk or paper backing—thus reducing application time.

Typical Applications

Fiberglas-Mica combination materials are used wherever there is a need for maximum reliability under high temperatures, either internal or external; where mechanical service is most severe, where a maximum safety factor is required. Its chief use is as ground or slot insulation in motors and generators, as phase insulation in large a-c apparatus, or as coil insulation between high and low voltage sides of dry-type transformers.

Complete Information

If you do not have complete information about Fiberglas-Mica combinations, write for the new EL 44-7 catalog, today. It also contains data on Fiberglas Tapes, Sleeving, Cord, etc. The name of the Fiberglas Insulation Materials Supplier located nearest to you will be supplied on request.

Owens-Corning Fiberglas Corporation, 1859 Nicholas Building, Toledo 1, Ohio.

In Canada, Fiberglas Canada Ltd., Oshawa, Ontario.

There is a **FIBERGLAS** Insulation Material for every need

Fiberglas-Mica Sheets or Tapes are available in thicknesses from .004" to .030"—with Fiberglas facings on one or both sides.

One of the chief uses of Fiberglas-Mica combinations is as ground or slot insulation in motors and generators.

Fiberglas-Mica has exceptional strength, permitting use of thinner tapes for conductor or coil insulation.

Write for catalog EL 44-7, today.

Each distributor of Fiberglas-base Insulation Materials has his own source of supply, since Owens-Corning Fiberglas Corp. does not process these materials.

FIBERGLAS

*T. M. Reg. U. S. Pat. Off.

ELECTRICAL INSULATION MATERIALS

the long eagerly awaited era is with us. Welcome though it may be, we cannot overlook the multitude of problems that this one word presents to the greater part of industry today. Due to the nature of our product, we of the JOHN C. DOLPH COMPANY, like a few others, have been fortunate in this respect. The minor problems that we have encountered have been overcome and we are now geared to devote our entire Research and Production Facilities to one purpose . . . aiding **you** in **your** post-war reconversion program. We do not know exactly what your program might be, but if you have need for Insulating Varnishes and Compounds in any part of your production cycle, **we do know** that our long experience, plus the many startling advances and new developments we have made in our field before and during the war, surely qualifies us to assist you. If you are interested in hearing first-hand about any new developments in this line, and at the same time have our skilled Service Engineers and experienced Laboratory Technicians placed at your disposal, without obligation, just fill in the coupon below. We can help you!

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Insulating **Dolph's** *Varnish Specialists*

JOHN C. DOLPH COMPANY

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Water Proof, Moisture Proof *and* Steam Proof METERS

VOLTMETERS . . . AMMETERS . . . MILLIAMMETERS . . .
MICROAMMETERS . . . WATTMETERS . . . BOTH AC AND DC

Now, you can get HICKOK precision and dependability in a new line of hermetically sealed meters. Available in 2½", 3½" and 4" round styles. Dimensions of American War Standards Assn. Drawings C39.2-1 and C39.2-2. The 4" size is built especially for use in radio service equipment where several scale arcs are required.

All instruments are hermetically sealed and both vacuum and pressure tested under water. Case fabricated of pressed steel and made corrosion resistant to meet specifications. Terminals are a special glass soldered-in type.

All meters are fully shielded, permitting use on either magnetic or non-magnetic panels. Operation is accurate and dependable even up to 85° centigrade. Internal pivot construction in D.C. types assures longer life and greater resistance to shock and vibration. Write for further information today.

THE HICKOK ELECTRICAL INSTRUMENT CO.
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PRECISION CALIBRATED . . . LASTING ACCURACY

An invitation to all electrical designers to

TRY SILVER GRAPHALLOY

FOR BRUSHES

High current density, low contact drop, low electrical noise, and self-lubrication are characteristics of this silver-impregnated molded graphite that may be the answer to your electrical brush problems.

FOR CONTACTS

Low contact resistance and non-welding when breaking surge currents are inherent properties of this unique combination of conductive silver and self-lubricating graphite.

SAMPLES of Silver Graphalloy will be gladly furnished for test on your applications. Silver Graphalloy is usually silver plated to permit easy soldering to leaf springs or holders. Why not WRITE NOW for your test samples?

ALWAYS SPECIFY GRAPHALLOY

GRAPHITE METALLIZING CORPORATION
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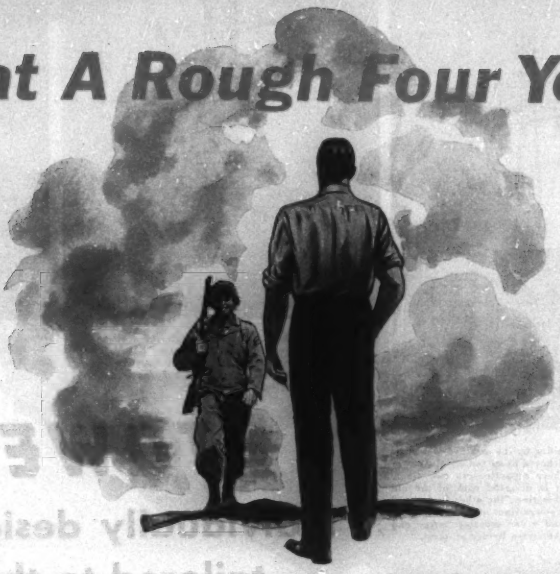
What A Rough Four Years



...And before we could take a deep breath, we were given another challenge—adapting *without delay* new developments, new techniques to civilian uses.

We like to think of our wires and cables as we think of the veterans now returning to civilian life. These veterans will not be the same people we sent off to war. They are battle-tested—they have grown up—they are ready to take on greater responsibilities than before.

Our wires and cables, too, are ready to take on new responsibilities. They have had to do jobs tougher than any wire ever faced . . . wherever the war took them—and it took them everywhere . . . moist, steaming jungle to bleak, frozen wastes. Whatever the conditions and demands—they came through the better for them.

What does this mean to the Electrical Industry? Just this. We are now ready to serve the Public Utilities and the broad program they are undertaking, the Electrical Manufacturer and his new products, the Electrical Engineer and his specialized needs, with a complete line of wires and cables that are better than ever.

Yes, it was a tough four years . . . we learned a lot . . . and now our new knowledge belongs to you.

U. S. ELECTRICAL WIRES AND CABLES

Serving Through Science

UNITED STATES RUBBER COMPANY

1230 SIXTH AVENUE • ROCKEFELLER CENTER • NEW YORK 20, N. Y.

Typical double-circuit tower carrying transmission lines over the roof of the power house. The unusual flare at the base provides direct connection and anchorage to existing roof trusses under the roof covering.

Double-circuit strain and angle tower, about 1 feet high, located between two existing subs tions and to clear storage yard conveyor syste

A tight-spot installation is typified by the new 113-foot angle tower at the extreme right. Anchored to its top are the power house double-circuits which here separate into two single circuits; one top-level circuit is diverted back of the old river crossing tower to the substation; the other is dropped some 30 feet and routed under power lines of the river crossing to the substation. The old river crossing tower and adjacent substation were also American Bridge projects.

TOWERS...

individually designed and tailored to the job!

A special type single-circuit, 57-foot, strain tower provides for an acute angular change in the transmission line from the power house to the substation.

DUE to increasing war loads, a recent expansion to generating capacity of an existing electric plant also involved the installation of additional circuit lines for distributing the new power to existing substations and main transmission lines.

The installation of supporting towers for the new circuits, because of limited ground space and overhead clearances imposed by existing structures and a complicated network of power lines, *and the need for quick action*, posed many unusual and difficult engineering and construction problems. All were satisfactorily solved, and with dispatch, by our tower department's technical staff in collaboration with the power company's engineers.

Because of the zigzagging course of the new circuits—around, over and under existing structures and power lines—each tower and its foundation were individually designed and tailored to prevailing site-conditions and to loadings from horizontal and vertical angular changes in alignment.

Pictured here are four of the many tower types designed and fabricated by American Bridge for this particular project. They are indicative of the accumulated experience and ingenuity of our tower engineers, and the fabricating and galvanizing resources of our tower plant.

In emergencies such as this, and when the time comes for postwar construction, both services are yours to draw upon.

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UNITED STATES STEEL

5,312 SOLUTIONS TO POST WAR RELAY PROBLEMS

Fit the relay to the job!

To make this readily possible, Struthers-Dunn offers 5,312 *standard* types, each available in countless design adaptations to fit your needs *exactly*. These include thousands of styles, shapes, sizes and ratings in a-c types, as well as hundreds more of the most modern d-c types including those capable of withstanding the rigors of war equipment usage.

Beyond the standard Struthers-Dunn types, at your service, are the full facilities of a large, specialized organization which, for 22 years, has concentrated exclusively on "tailoring" relays and timers to specific applications and requirements.

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Relay and Timer Specialists Since 1923

DISTRICT ENGINEERING OFFICES: ATLANTA • BALTIMORE • BOSTON • BUFFALO • CHICAGO • CINCINNATI • CLEVELAND DALLAS • DENVER • DETROIT • HARTFORD • INDIANAPOLIS • LOS ANGELES • MINNEAPOLIS • MONTREAL NEW YORK • PITTSBURGH • ST. LOUIS • SAN FRANCISCO • SEATTLE • SYRACUSE • TORONTO

THEY'LL HELP YOU BUY AND USE CAPACITORS . . . *EFFICIENTLY!*

Up-to-the-minute CAPACITOR and APPLICATION DATA

HIGHER POWER IN LESS SPACE

with this new 200° C. Class C Insulation

Manufacture coils, transformers, or similar wire wound devices? Then you owe it to yourself to investigate the tremendous possibilities of *CEROC 200—the Sprague inorganic, non-inflammable wire insulation that permits continuous operation to 200° C.

Write for Bulletin 503

A lot of time and effort has gone into making these new Sprague Catalogs invaluable guides to modern Capacitor selection and use for all who buy or use Capacitors.

CATALOG 10 brings you up-to-the-minute data on time tested *Sprague Dry Electrolytic* types for practically any application. *CATALOG 20* does the same relative to the most modern line of *Paper Dielectric Capacitor* types on the market today. A copy of either or both will gladly be sent on request.

Write Today!

SPRAGUE ELECTRIC COMPANY • North Adams, Mass.

SPRAGUE

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CAPACITORS – KOOLOHM RESISTORS

OHMITE

ALL CERAMIC • HIGH CURRENT

Tap Switches

IN 5 SIZES

MODEL 212
15 AMPS. MAX. 150 V.A.C.
DIAMETER 2-1/4"
2 to 12 TAPS
2 or 3 Units Can Be Connected in Tandem
for Simultaneous Circuit Switching

FEATURES

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- Compact, All-Enclosed
- Slow-Break, Quick-Make
- Silver-to-Silver Contacts
- Self-Cleaning Action
- Low Contact Resistance
- Cam & Roller Mechanism
- High Strength Ceramic Hub
- Insulated Steel Shaft
- Back-of-Panel Mounting

Write on company letterhead for Industrial Catalog and Engineering Manual No. 40. Address Ohmite Mfg. Co., 4801 Flournoy St., Chicago 44.

Simpler, More Compact

HIGH CURRENT CIRCUIT SWITCHING

In these Ohmite load-break switches, as few as 2 or as many as 12 high current taps are compactly arranged yet perfectly insulated. The switches are non-shorting, single-pole, rotary, multi-position units. They provide greater operating convenience in battery chargers, tapped transformers, welders, induction heaters, and other applications. *Write for further helpful facts or engineering aid.*

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Be Right with **OHMITE**

RHEOSTATS • RESISTORS • TAP SWITCHES

PERMANENT MAGNETS MAY DO IT BETTER

Photograph of a fragment of Alnico V

(This is the third of three advertisements regarding permanent magnet materials)

What is your magnet made of?

ALNICO V

If your product requires a permanent magnet that develops the maximum magnetic energy in limited space and weight, Alnico V is the solution. It is the newest and "strongest" of the Alnicos, the aluminum-nickel-cobalt-iron permanent magnet alloys. Its store of magnetic energy is about five times that of cobalt magnet steel and three times that of the other grades of Alnico. Of the permanent magnet materials commercially available, it is highest in residual induction as well as available energy. Like the other Alnicos, No. V is hard, brittle, non-forgeable and non-machinable and is formed by casting.

The improved permanent magnet characteristics of Alnico V are obtained by using a higher percentage of cobalt and lower percentages of the other elements and a new heat treatment. The treatment consists of normalizing at a much higher temperature than with the other grades, cooling in a magnetic field parallel to the field in the finished magnet and annealing for several hours.

Utilization of the maximum available energy requires that both magnet and magnetic circuit be designed with expert consideration of the magnetic characteristics of Alnico V. For over 35 years, this company has specialized in permanent magnet engineering and production. We invite the consultation of manufacturers who have problems in the use or application of permanent magnets. Write for free technical handbook: *Permanent Magnet Manual.*

★★★ THE INDIANA STEEL PRODUCTS COMPANY ★★★

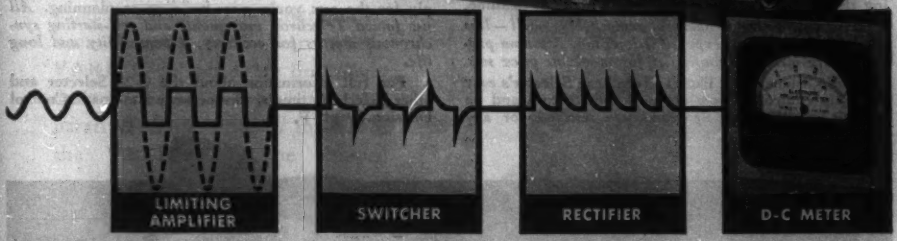
6 NORTH MICHIGAN AVENUE, CHICAGO 2, ILLINOIS

Copr. 1945, The Indiana Steel Products Co.

SPECIALISTS IN PERMANENT MAGNETS SINCE 1910

LABORATORY INSTRUMENTS FOR SPEED AND ACCURACY

What Happens Inside an -hp- Model 500A Frequency Meter



This Instrument Counts Cycles of an Unknown Frequency

The above diagram shows how the *-hp-* 500A analyzes an unknown frequency so that cycles per second will accurately register on the specially calibrated d-c meter.

The unknown frequency is introduced to a limiting amplifier which generates a square wave output. The square wave voltages are applied to two switching tubes which become alternately conducting on opposite half cycles. From a constant current supply, the two switching tubes deliver a current to load resistors. Each load resistor causes the charge on a pair of capacitors to vary in accordance with the switched current pulses. Thus a current flows from the combination to the rectifier. The rectified pulses are delivered to the d-c meter. Each pulse is of the same size and independent of other factors. The meter integrates these pulses and gives a deflection which is proportional to the number of pulses per second. Thus the meter reading is directly related to the unknown frequency.

The instrument is easy to use and requires but a small amount of power. It has good sensitivity and a wide range of usable voltages. The input range is from 0.5 to 200 volts—input impedance is 50,000 ohms. A switch on the panel selects one of ten ranges which are read directly on the meter.

Accuracy of the instrument is ±2%—independent of line voltages, vacuum tube characteristics and magnitude and wave form of applied voltage—because the meter reading is dependent only upon the constant current supply and the RC combination.

The uses for this meter become readily apparent. Of special interest is its use as a high speed tachometer. (See column at right.) Write for more detailed information today. *-hp-* engineers are at your service.

HEWLETT-PACKARD COMPANY

BOX 1073B · STATION A · PALO ALTO, CALIFORNIA

Audio Frequency Oscillators *Signal Generators* *Vacuum Tube Voltmeters*
Noise and Distortion Analyzers *Wave Analyzers* *Frequency Meters*
Square Wave Generators *Frequency Standards* *Attenuators* *Electronic Tachometers*

You can measure 3,000,000 r.p.m. with this -hp- Electronic Tachometer

Using a photo electric cell pickup in conjunction with an *-hp-* Model 500A Frequency Meter provides an Electronic Tachometer capable of accurately measuring incredible speeds. This method places no load on the device being clocked.

Two special models of *-hp-* frequency meters, complete with light source and pickup, are available for this purpose. One model (505A) is calibrated in r.p.m. from 600 to 3,000,000 r.p.m.; the other model (505B) is calibrated in r.p.s. from 50 to 50,000 r.p.s. Speeds as slow as 600 r.p.m. (10 r.p.s.) are conveniently measured directly, while still slower speeds can be measured by a simple expedient.

Ask for special technical bulletin on *-hp-* Models 505A and 505B.

1073

Boost radio sales with built-in Telechron Selectors

HERE'S a double-duty timer to give your radio receivers the *extra* appeal needed for successful post-war selling. It's *much more* than an absolutely accurate electric clock. It turns on the set automatically at any pre-selected time in the morning to waken the owner with music. It switches the set on for favorite programs during the day and evening—then shuts it off at bedtime.

The cost to set makers is remarkably small—less than $4. Installation expense is low, too. Volume producers are already choosing it for moderate-price sets.

Radio listeners will like the Telechron Selector's easy finger-tip control. There are no knobs to turn and no difficult calculations. Programs are selected for any 15-minute period by flipping out one of the 48 keys around the large, legible clock dial. Keys are automatically reset to "off" position after timing periods are passed. Programs can be selected 10 hours in advance.

The C-28 Telechron Selector is only one of the full line of automatic timing and control devices we can supply for the sets you're now building or planning. *All use famed Telechron movements and self-starting synchronous motors for accuracy, dependability and long life.*

For full information about the C-28 Selector and other Telechron timers, wire or write Automatic Control Division, Dept. F.

Telechron

REG. U. S. PAT. OFF.

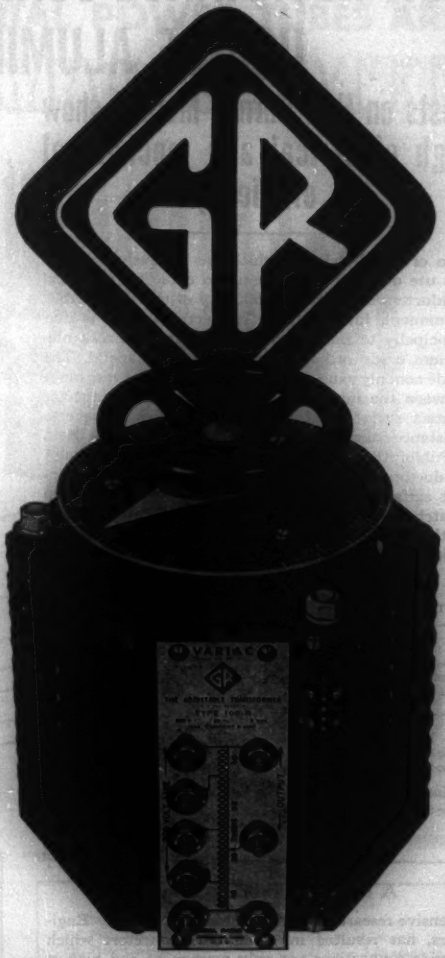
WARREN TELECHRON COMPANY • ASHLAND, MASSACHUSETTS

MORE VARIACS* NOW!

A portion of our greatly expanded VARIAC production has been released from war orders. VARIAC deliveries are improving daily. We hope that within a comparatively short time *all* models of the VARIAC can be shipped promptly upon receipt of your order.

In the meantime you'll find several weeks required for delivery of some models well worth the waiting . . . VARIACS are still the *original* continuously-adjustable autotransformer first introduced by General Radio . . . redesigned to meet all of the mechanical and electrical requirements for all types of service... assuring rugged construction, long life and the same manufacturing care that is given to the finest G-R laboratory instrument.

You may have to wait a little longer for VARIACS, but you'll be satisfied many times longer.



YOU CAN GET THESE FROM STOCK At the moment we have a small stock of the popular Types 100-Q and 100-R VARIACS and can ship immediately. These models are rated at 2,000 va. The Type 100-Q supplies continuously adjustable voltages from zero to either 115 or 135 volts from a 115-volt 60-cycle line with a maximum output of 18 amperes; the Type 100-R supplies a maximum of 230 or 270 volts from either a 230- or 115-volt line with a maximum current rating of 9 amperes from a 230-volt input, or 4.5 amperes when used on 115 volts. Price of either model: $40.00.

VARIAC

** The trade name VARIAC is registered at the U. S. Patent Office. VARIACS are manufactured and sold only by General Radio Company under our U. S. Patent 2,009,013.*

MADE ONLY BY **GENERAL RADIO COMPANY** Cambridge 39, Mass. NEW YORK CHICAGO LOS ANGELES

LOW-RESISTANCE CONNECTIONS FACILITATE USE OF ALUMINUM CABLE!

Tests on New Burndy Method show high electrical and mechanical efficiency

One of the drawbacks which has seriously retarded the use of small-sized aluminum cable for electrical conductors has been the difficulty of making reliable, permanent, low-resistance connections. This is due principally to the tenacious, transparent film of aluminum oxide ordinarily present on the metal. The oxide not only causes extremely high contact resistance between the outer cable strands and the connector contact surface, but it also causes high transverse resistance from strand to strand within the cable itself.

Public utilities and other users of large-size aluminum conductors have solved this problem by coating contact surfaces with a protective compound and then scratch brushing to break up the oxide film. This method is impractical, however, with small cables which have a large number of small strands, and where the connectors used have small barrels.

Table showing effect of treatment on connection resistance

Treatment of Terminal Contact Surface	Method of Using Compound Filler	Resistance in Microhms		Relative Conductivity, %
		Connection Resistance	Equal Length Cable	
None	None	136.41	81.74	59.8
Zinc-flashed	None	91.92	81.74	88.9
Zinc-flashed	Contact surface compound coated	78.75	81.74	103.8
Zinc-flashed	Compound forced between cable strands	69.57	81.74	117.5

A Practical, Efficient Solution

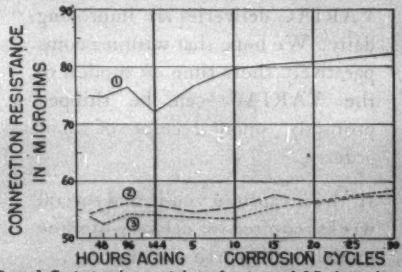
Intensive research on this problem by Burndy Engineers, has resulted in aluminum connectors which provide connections not only permanent and high in electrical efficiency, but also practical from the standpoints of convenience and over-all costs. In fact, installation procedure remains identical with the present rapid method of indenting small wire connectors with a Burndy Hytool.

In manufacture, the surfaces of these new Burndy aluminum connectors are etched chemically, and while the oxide-free surfaces are still wet, they are zinc flashed, and later plated with zinc to provide a mechanically strong coating. Thus, the reformation of the oxide film is prohibited.

The barrel of each zinc-plated connector is then filled with a special compound of zinc dust suspended in petrolatum jelly. Thus, when the cable is inserted into the zinc-compound-filled barrel, and the connector is indented to the cable with a Burndy Hytool, the compound is forced down between the strands of the cable. This breaks through and disperses the oxide film on the individual strands, and prevents further formation of oxides or other products of corrosion.

As will be noted from the table, the electrical conductivity of the finished connection is practically double that of an ordinary non-treated aluminum connection.

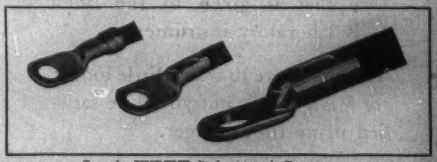
Effect of corrosion on electrical resistance of connections



Curve 1. Contact surfaces not cleaned, not coated. 2 Surfaces cleaned and coated with compound. 3 Surfaces zinc flashed and coated with compound.

The curve shows clearly the ability of these new Burndy connectors to maintain a low resistance after exposure to corrosive agents.

It should be remembered, however, that the most satisfactory method of connecting aluminum cables is by the longitudinal indent method. For only this type of indent forces the individual strands to shift and rearrange themselves, thus exerting a wiping action on each other which helps to remove the oxide film.



Burndy HYDENT (indent-type) Connectors

Laboratory Report Available

A complete laboratory report on this new Burndy method of connecting aluminum cables has been prepared and copies can be secured by writing to Burndy Engineering Company, 107-E Bruckner Blvd., New York 54, N. Y.

Federal INDUSTRIAL POWER TUBES ARE PERFORMANCE-RATED

Federal Industrial Power Tubes are rated on the basis of actual performance under the same severe operating conditions found in industry . . .

Not from nominal design center values nor from operation under ideal conditions . . . but from actual tests in industrial heating equipment operating with and without work in the load circuit.

Federal tests include conditions where the character of the work changes during the heating cycle and each exacting test is designed to assure long service and economical performance from every tube that bears the name . . . Federal.

Write for information about Federal's "better" industrial power tubes.

TECHNICAL DATA FOR TYPE F-7C25

Maximum Ratings for Maximum Frequency of 50 Mcs.

DC Plate Voltage	3500 volts
DC Plate Current	1.25 amp.
Plate Dissipation	2500 watts
Filament Voltage	11.0 volts
Filament Current	27.5 amps.
Overall Height	app. 7"
Maximum Diameter	3½"

Supplied with 6" flexible copper leads, 2 on each terminal

Type of Cooling	Forced air

(Also supplied for water-cooling, type F-5302)

Federal Telephone and Radio Corporation

A Unit of I.T.&T.

Newark 1, N. J.

ELECTRONICS DESIGNER'S

WATER-COOLED CAPACITORS FOR HOT JOBS

Substantial savings are made possible by the small space requirements and low price of G-E high-frequency, parallel-plate capacitors. These compact, water-cooled, liquid-filled units are designed especially for use in the resonant circuit of high-frequency electronic oscillators, such as those used in electronic-heater equipments. Features include: low losses at high frequencies, uniformly high dielectric strength, and high current rating per unit volume.

Available in ratings of .0075 to .034 microfarad (capacitance tolerance 5%), and for maximum rms working voltages of 2000 to 9000 volts. Write for Bulletin GEA-4365.

MIGHTY RESISTORS OF G-E MYCALEX

Physically stronger than porcelain — except under compression — G-E mycalex has higher heat and arc resistance than organic insulating materials; at elevated temperatures its dielectric strength is also higher. It is compression-molded into plates, rods, and strips that can be readily machined to finished shapes. Simple shapes are injection-molded directly, with or without metal inserts.

Its low loss at high frequencies makes G-E mycalex particularly valuable in uhf apparatus. Impervious to water, oil, and gas, G-E mycalex neither warps nor shrinks with age. Write for Bulletin GEA-4244.

TO TEACH ELECTRONICS QUICKLY

Where production workers and foremen have a working knowledge of electronics, production steps up because there are fewer rejects, and less time is spent on repairs. Now you can teach them all the fundamentals without the monumental task of preparing such a course. General Electric offers a talking slidefilm course to teach not only the fundamentals, but also principles of combining tubes and other components into electronic circuits. It is written for easy understanding by personnel lacking a technical background.

Twelve half-hour slidefilms with records, complete in a carrying case, make up the entire course. A meeting place, screen, and a sound slidefilm projector (35mm, 33⅓ rpm) are all you need. With the 12 slidefilms you get 25 sets of individual lesson guides keyed to the film, and a manual containing instructions for conducting the course. Write for details.

FROM 0 TO 270 VOLTS AT A TWIST OF THE WRIST

For jobs that need smooth, uninterrupted control of voltage and small amounts of power, the G-E variable-voltage autotransformer is finding wide application. Maximum output voltage is 270 from a 230-volt power source; half that from 115-volt power supply.

Output voltage is varied by moving a carbon brush around a band on the coil from which the tough insulation has been removed. Calibrations on the easy-to-read dial are widely spaced for easy selection of the output voltage. Strong mechanical construction, light weight, and small size make this G-E variable-voltage autotransformer ideal for bench or panel mounting. Ratings from 243 to 810 va. Write for Bulletin GEA-3635A.

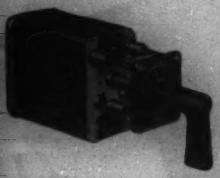
COILS FORM FASTER WHEN YOU USE FORMEX

High-speed winding, bonding, and baking pose no problem with Formex magnet wire. Its abrasion resistant, polyvinyl-acetal insulation — a tough, flexible film — will turn sharp corners at high speed without cracking. Formex wire speeds up production, cuts down factory rejects and customer complaints.

The dielectric strength of Formex magnet wire is high and stays high, during the entire life of your apparatus. For tighter-packed, lighter-weight, lower-cost coils, specify Formex magnet wire, either regular or colored. It's suitable for operation in ambient temperatures up to 105 C — also for jobs where moisture and solvent resistance are needed. Round Formex from 8 Awg to 40 Awg, ultra-fine from 41 Awg to 50 Awg, and rectangular in a full range of sizes. (Bulletin GEA-3911)

GENERAL ELECTRIC

DIGEST



ONE MOTION CONTROLS MANY CIRCUITS

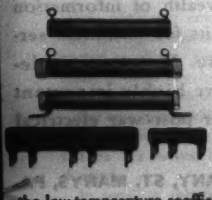
For transfer and control switching, simple or complex, there is a G-E (Type SB-1) switch to do the job. These switches are rated 600 volts, 20 amp continuous or 250 amp for 3 seconds. Standard models are available with as many as 16 twelve-position stages. Precision construction makes operation easy, even in special models which have as many as 40 stages. Cam-operated silver contacts are long-lived, proved by more than 1,000,000 test operations without excessive wear. Stages are isolated by dielectric barriers.

Wiring requires only a screwdriver, and ample space is allowed for easy connection. There are two types of locks, both of which permit locking in any position. The standard switches are dead-front, with all live parts protected by a removable cover. Write for Bulletin GEA-1913-D.

WHEN DELAY HAS A JOB TO DO

This flux-decay, copper-jacketed time-delay relay is specially designed for application in aircraft where small size, reliability, and light weight are of importance.

A time delay of .35 sec is provided. A variety of contract arrangements is available for handling up to 100 amps (inrush current) under the usual conditions of altitude, temperature, vibration, and humidity. Write for Bulletin GEA-3865.



HOT BUT NOT BOTHERED

Wound on strong, heat-resistant bodies, G-E vitreous-enameled resistors are little affected by sudden, extreme, temperature changes. From 10 to 180 watts, they are available in most resistance ratings. Resistance remains practically constant, because of the low temperature coefficient of the resistance wire.

Enamel, fused to a uniform, glassy surface over the wire imbedded in it, forms a durable, water- and air-impervious coating. A wide variety of open and closed styles, terminals, taps, and mountings gives these resistors a broad field of application in electronic apparatus. Write for Bulletin GEA-3911.

Timely Highlights on G-E Components

Capacitors • Sensitive control and time-delay relays • Limit switches • Motors, dynamotors, amplidynes • Motor-generator sets • Alnico magnets • Small panel instruments • Formex magnet wire • Radio transformers • Switchettes • Selsyns • Chokes • also tubes, crystals, plastics products, insulation materials, and many other

GENERAL ELECTRIC COMPANY,
Apparatus Dept., Sec. 643-9
Schenectady 5, N. Y. 8010

Please send me

- GEA-4365
- GEA-4244
- GEA-3911
- Details on Electronics Course
- GEA-3865
- GEA-3635A
- GEA-1913D

NAME

COMPANY

ADDRESS

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TACT DATA

... just off the press!

If your product uses contacts you'll find in this new Stackpole Contact Catalog a wealth of information designed to help you select units for maximum service under all conditions of use. New contact developments described will prove highly important in the design of smaller, better post-war electrical equipment. Write today!

STACKPOLE CARBON COMPANY, ST. MARYS, PA.

WRITE FOR YOUR COPY TODAY!

STACKPOLE

BRUSHES and CONTACTS (All carbon, graphite, metal and composition types)
RARE METAL CONTACTS • IRON CORES • WELDING CARBON PRODUCTS
PACKING, PISTON AND SEAL RINGS • RHEOSTAT PLATES AND DISCS
BATTERY CARBONS • POWER TUBE ANODES • CARBON PIPE, ETC.

WESTON CAN TELL YOU LOTS

That's NEW about Sensitive Relays!

Many engineers concentrating on specialized wartime problems have had little opportunity to keep posted on all new developments in the electrical field. Many of these developments, too, could not previously be revealed for security reasons.

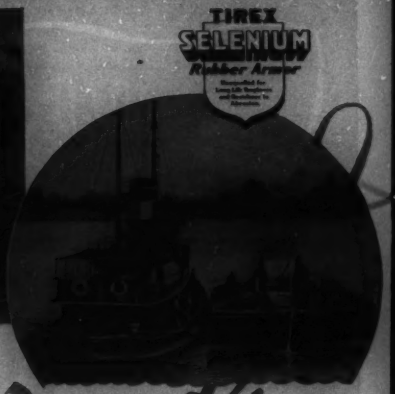
But now, with civilian activities in closer sight, these engineers will want to find out how far electrical science has moved forward in the years they have skipped.

In sensitive relays, for example, much has happened which will be of vital importance to design engineers. New sensitivities have been achieved by WESTON . . . making available relays that provide positive control on extremely minute quantities of electrical energy. New compactness has been achieved, too; overcoming former space limitations through extremely small-size and light-weight.

To make sure that your post-war products, or manufacturing processes, are not handicapped by lack of knowledge about these new sensitive relay developments, ask the WESTON representative in your vicinity to quickly bring you up-to-date. Or, write direct to . . . Weston Electrical Instrument Corporation, 664 Frelinghuysen Avenue, Newark 5, New Jersey.

Weston Instruments

ALBANY • ATLANTA • BOSTON • BUFFALO • CHICAGO • CINCINNATI • CLEVELAND • DALLAS • DENVER • DETROIT • JACKSONVILLE • KNOXVILLE • LOS ANGELES • MERIDEN MINNEAPOLIS • NEWARK • NEW ORLEANS • NEW YORK • PHILADELPHIA • PHOENIX • PITTSBURGH • ROCHESTER • SAN FRANCISCO • SEATTLE • ST. LOUIS • SYRACUSE
In Canada, Northern Electric Co., Ltd., Powerlite Devices, Ltd.



UNDERNEATH Old man River

THESE pictures illustrate the laying of a 3-conductor # 4/0 rubber insulated submarine power cable built recently for one of the Southern power companies. The cable is being laid on the bottom of the Mississippi River. It will be used to supply power to the war industries located on the opposite bank of the Father of Waters.

It was natural for the power company in question to turn to Simplex to help engineer and manufacture this cable, because Simplex tailor-made cables are known far and wide for their dependability and long service life.

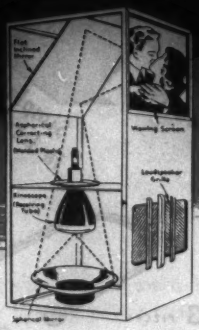
It is these intrinsic qualities in all Simplex cables that make them so desirable. When you need help in designing power cables rely on the Simplex Engineering Department. Their wide experience is at your service and there is no obligation.

Simplex Wire & Cable Co., 79 Sidney Street, Cambridge 39, Mass.

Simplex

WIRES and CABLES

HERE'S WHAT YOU'LL GET FROM RCA IN PROJECTION-TELEVISION TUBES...



LOWER COST OF TUBES: Simple bulb design in soft glass lends itself to low-cost quantity production.

LOW-COST POWER SUPPLY: New electrostatic-focus electron gun avoids cost of a magnetic-focus coil and, at the same time, permits use of a low-cost power supply not requiring good regulation.

HIGH CONTRAST: New "settling" method of applying screen reduces degree of optical contact between fluorescent particles and face of tube, resulting in higher contrast.

TAILORED TO PROJECTION OPTICS: Spherical face of RCA projection kinescopes matches RCA reflection-type optical system.

* * *

Already, RCA has demonstrated to hundreds of engineers and radio experts television of tomorrow as made possible by these new tubes. Screens as large as a newspaper page, with clear, bright images, enable dozens of persons to see the program . . . and this is but one example of RCA electron-tube development, engineering and leadership.

Postwar, why not consult RCA for better tubes for better television? RCA tube-application engineers are always ready to serve you. Address: RCA, Equipment Sales Department, Section 62-34A, Harrison, N. J.

RADIO CORPORATION OF AMERICA

RCA VICTOR DIVISION · CAMDEN, N. J.

The Fountainhead of Modern Tube Development is RCA

IT'S HERE— Copperweld

A New and

COMPLETELY PREFORMED INSULATOR TIE

for use with Copperweld and Copperweld-Copper Conductors

Inexpensive

Simple in Design

Easy to Install

Reinforces Conductor

Increases Conductor Life

JUST 3 PIECES— ONE BINDING WIRE AND TWO SPIRALS
WRAP SPIRALS ON CONDUCTOR— INSERT BINDING WIRE THROUGH LOOPS OF SPIRALS
TWIST ENDS OF BINDING WIRE TO TIGHTEN—THAT'S ALL!

Manufactured by

COPPERWELD STEEL COMPANY

Glassport, Pa.

GRIP-FLEX 45

Builders and operators of overhead power lines will welcome the new Copperweld Grip-Flex 45 insulator tie—simple, inexpensive and easy to install. Enables every lineman to do a uniform tying job because it substitutes for uncertain care and skill the machine precision of a few factory preformed parts.

Copperweld Grip-Flex 45 is the ideal insulator tie for Copperweld and Copperweld-Copper Conductors, for both top and side tying. It provides a floating support for the conductor—the reinforcing wires keep the conductor away from the insulator. The binding wire does not touch the conductor. Strong holding power against unbalanced line tension is assured. *These ties fully meet the requirements of the National Electrical Safety Code.*

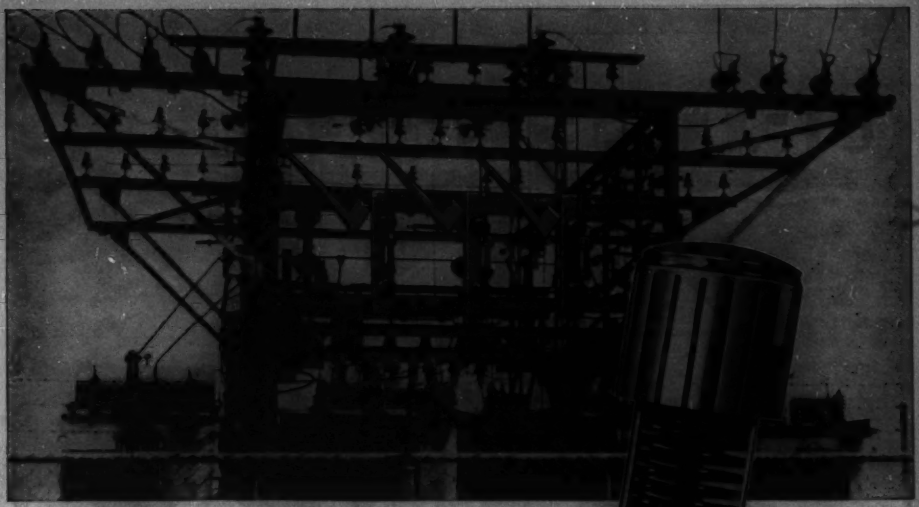
Copperweld Grip-Flex 45 is new—but not untried. Extensive tests in Copperweld's laboratory show this tie to be a distinct improvement over hand wrapped ties. It takes less time to apply—develops greater holding power—increases conductor life—and assures uniformly good results.

Write today for complete details.

Copperweld

Sold by

ANACONDA WIRE & CABLE COMPANY, NEW YORK, N. Y.
COPPERWELD STEEL COMPANY, GLASSPORT, PA.
KENNECOTT WIRE & CABLE COMPANY, PHILLIPSDALE (RUMFORD), R. I.
PHELPS DODGE COPPER PRODUCTS CORPORATION, NEW YORK, N. Y.



Still The Preferred Power Fuse—1944 Installations Again Exceeded Previous Year

Records for 1944 reveal continued increases in installations of S & C Liquid Fuses.

Discriminating engineers of our important power companies are well aware of the many years of reliable, economical protection provided by these Fuses of high current interrupting ratings. These men recognize the value of accuracy of time current characteristics—the non-corrosive character of the pure silver fusible elements,—the fast clearing of fault currents,—and the ease of inspection from the ground. Send for Bulletin 200-B.

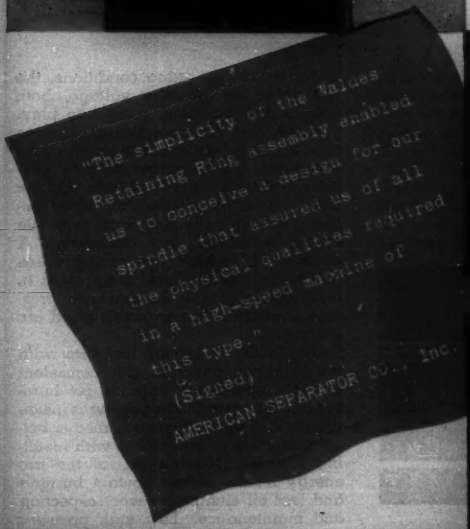
Liquid FUSES

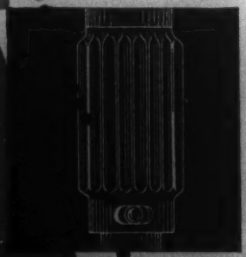
¼ to 400 Amps., 7500 to 138,000 Volts.

SCHWEITZER & CONRAD, Inc.
4427 Ravenswood Avenue, Chicago 40, U. S. A.
Represented in Principal Cities (Consult Telephone Directory)
In Canada by Powerlite Devices, Ltd., Toronto, Ont.

another proof

that Truarc Retaining Rings hold moving parts together better!


"The simplicity of the Waldes
Retaining Ring assembly enabled
us to conceive a design for our
spindle that assured us of all
the physical qualities required
in a high-speed machine of
this type."
(Signed)
AMERICAN SEPARATOR CO., Inc.



BEFORE TRUARC

The American Separator Company found no solution to the problem of excessive noise and vibration set up by the spur gear train action of this separator bowl revolving at 8500.

AFTER TRUARC

Truarc Retaining Rings eliminated vibration and noise while actually simplifying the assembly, achieving a rigid bearing of greater strength with no loss of speed!

If your problem is holding together or positioning moving parts, you should know Truarc Retaining Rings. They offer important advantages over nuts, shoulders, collars and pins. They save space. They make assembly and disassembly easier, simpler, quicker. They keep their bulldog grip, hold their true circularity indefinitely under severe working conditions. Test Waldes Truarc in your products, in the machines that make them. Write for samples and complete data. Dept. F-10.

WALDES TRUARC RETAINING RING

WALDES KOHINOOR, INC., LONG ISLAND CITY 1, NEW YORK

CANADIAN REPRESENTATIVES: FRENCH PRODUCERS CORP., LTD., 72-74 STAFFORD STREET, TORONTO

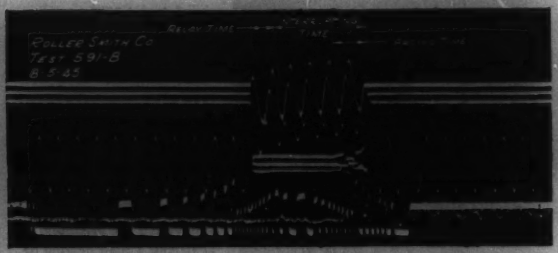
U. S. PAT. RE-18,144

ROLLER SMITH

"ON THE LINE" TEST STATION PROVIDES KEY TO SECRETS OF ARC EXTINCTION

THE new Exotherm principle of arc extinction discovered by Roller-Smith engineers puts arcs out faster because it harnesses the properties and energy of the gases produced when the arc is struck.

The discovery of the Exotherm principle grew out of the efforts of Roller-Smith engineers to reconcile conventional laboratory tests of breakers with performance "On the Line." The only answer seemed to be "On the Line Testing" of breakers. Through cooperation of the utility industry the first "On the Line" test station of its kind was established by Roller-Smith to seek out the real facts about oil circuit breaker performance. Because the tests were conducted under actual operating conditions, the full value of recovery voltage, both normal and transient, came into play. For the first time conflicting theories and claims about arc extinction could be tested under actual service conditions. After hundreds of tests "On the Line," provided information never before available, the Exotherm principle of arc extinction was discovered. A chamber in which the arcing takes place confines the gas, compresses it, and correlates the thermal and pressure characteristics to obtain rapid arc extinction.



Typical test oscillogram of Roller-Smith oil circuit breaker employing Exotherm principle. Note 5 cycle interrupting time.

Roller-Smith oil circuit breakers with the Exotherm principle give consistent 5 cycle operation; little or no burning of contacts and low pressures inside the tank. 5 cycle operation means better protection to equipment with resulting savings. Making use of the arc energy results in less contact burning and less oil sludging, saves inspection and maintenance. Low tank pressure results from the Exotherm principle because the gas is cooled and contracted before it gets into the tank. The result —far greater safety for indoor operation than ever before.

For full information on the Exotherm principle applied to Roller-Smith oil circuit breakers, write to dept. EE.

ROLLER SMITH

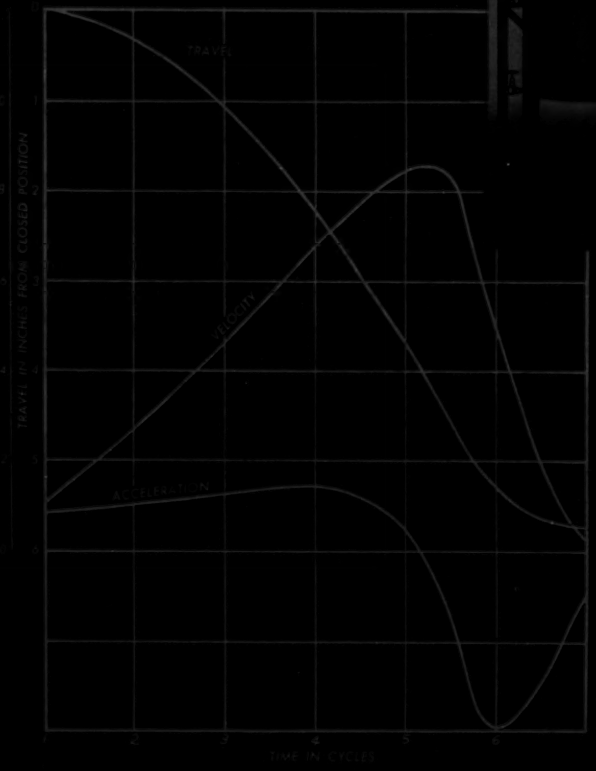
Oil Circuit Breakers

BETHLEHEM • PENNSYLVANIA

In Canada: Roller-Smith Marsland, Ltd., Kitchener, Ontario

STANDARD AND PRECISION ELECTRICAL INSTRUMENTS • AIRCRAFT INSTRUMENTS • SWITCHGEAR
AIR AND OIL CIRCUIT BREAKERS • ROTARY SWITCHES • RELAYS • PRECISION BALANCES

Announces


TRAVEL
VELOCITY
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TRAVEL IN INCHES FROM CLOSED POSITION
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SELF CONTAINED 2300 VOLT OIL IMMERSED A.C. INDUCTION MOTOR CONTROL

CONSTRUCTION AND OPERATING FEATURES

1. They have an especially designed, quick-acting, heavy-duty contactor.
2. High interrupting disconnect fuses, hook stick operated.
3. Self-contained, seal-off motor terminal compartment.
4. Centralized self-contained low voltage control terminal compartment.
5. Magnetic overload relays with electric reset, instantaneous and inverse time element.
6. Self-contained control potential transformer.
7. Self-contained Tank lowering device.
8. Insulated Bus, supported on porcelain Insulators.

The simplicity, efficiency, and flexibility of this Push Button operated Control have been made possible by Rowan Engineers after thirteen years of research, and production of this type of equipment. It has been designed for Engineers whose prime thoughts are safety, continuous operation, minimum installation and maintenance cost. These starters are floor mounted and are arranged for single or group installation. They are Push Button operated; of the full voltage or reduced voltage type; arranged for indoor, or outdoor service; are of cubicle construction and are complete within themselves. *Let us have your 2300 Volt control problems.*

ROWAN CONTROL

Here's How Resistance Welding Pays:

Weld-O-Trol and weld-and-sequence timer added to this welder brought a net saving of $23,960.05 in production of blower units.

This large electrical manufacturer reaped a $23,960.05 dividend from two electronic units that put resistance welding to work on his production line.

To begin with, he invested $493 in this electronic equipment... a Westinghouse Weld-O-Trol and an automatic weld-and-sequence timer. These controls were added to a welder whose original cost was $2,020, making a total outlay of $2,513.

The unit was then used to resistance-weld two types of double-sided blowers, which included welding 24 vanes on each side of the main circular sheet and a reinforcing ring welded to the vanes on the outside. The blowers, made of ⅛" mild steel, were formerly welded by a slower process.

How well resistance welding speeded the operation is shown by the savings in labor costs over a period of one year in producing 4,155 units ...a total saving of $26,473.05! Subtract the investment and the manufacturer still pocketed $23,960.05... a gift of resistance welding to his recognition of the high ability of this electronic welding process.

The results of this remarkable history are nothing new to users of resistance welding familiar with the wide flexibility of this modern production tool. Ask your nearest Westinghouse office to show you how resistance welding control can work in your plant. Westinghouse Electric Corporation, P. O. Box 868, Pittsburgh 30, Pa. J-21345

Westinghouse

Electronics at Work

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This specialization also gives you the latest in transformer design. It is the keystone of AmerTran's forty-four years of progress in transformer manufacture. A letter outlining your problem may mean solving it.

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Pioneer Manufacturers of Transformers, Reactors and Rectifiers for Electronics and Power Transmission

LINE POST LINES ARE GOOD LINES

Because

THEY REQUIRE LESS CLEANING

To provide fog-type corrugation was a primary consideration in the original Line Post design. This multi-petticoat arrangement provides a *uniform* leakage path, not subject to the "hot-spots" that cause so much failure of conventional insulators. Wind and rain go a long way toward keeping the Line Post and Station Post clean, and even under worst conditions, cleaning can be reduced to a very infrequent routine.

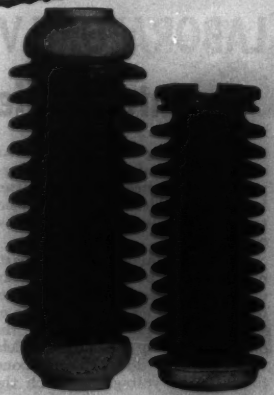
Lapp

LINE POSTS ARE GOOD INSULATORS

Because of

VACUUM PROCESS PORCELAIN and SPECIAL LAPP TECHNIQUE

Until Lapp's success of Line Post and Station Posts was an evident accomplishment, this design was "impossible of efficient production" in American ceramic plants. Lapp's ability to produce Posts as well as other difficult ceramic shapes is due to original Lapp techniques. One of these is Vacuum Process, a method whereby air, both as bubbles and in solution, is removed early in the clay-handling procedure. Subsequent operations of pugging, throwing, jiggering, plunging and turning are thus made possible, without danger of laminations, weaknesses or cracking. The same techniques which made Lapp Post insulators possible are back of Lapp's promise for *better porcelain for all your insulator requirements.*



Lapp

LAPP INSULATOR COMPANY, INC., LE ROY, N. Y.

write for new bulletin ACV-102

LABORATORY VOLTAGES accompany your equipment into the field with built-in CONSTANT VOLTAGE

On the drafting boards of hundreds of sales-minded design engineers, product insurance is being written into the specifications of new electronic and electrically operated equipment.

A critical analysis of sales department records of past performance usually discloses that the most frequent cause of equipment failure or sub-standard performance is the one most often overlooked — field voltages that do not correspond to the rated voltage at which the equipment is designed to operate.

Today sales-minded design engineers make certain that carefully controlled laboratory voltages, on which the operation of their equipment is predicated, go with it into the field, by writing "SOLA Constant Voltage Transformers" into their design specifications. In many cases the inclusion of the "CV" transformer is accomplished at an actual saving in cost over standard equipment design.

Thus rated voltage is available at all times because SOLA Constant Voltage Transformers instantly correct fluctuations as great as 30% to less than ±1% of rated requirements. These sturdy, automatic transformers require no pampering or supervision. They protect both themselves and the equipment against line surges and short circuits.

Standard units are available in capacities from 10VA to 15 KVA or special units can be built to your specifications.

Constant Voltage Transformers

SOLA

Don't forget to write for Sola's new Bulletin

Ask for Bulletin ACV-102

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These MULTIPRESS savings are typical. Its performance in scores of plants on dozens of operations proves that MULTIPRESS is Industry's New Tool of amazing advantages.

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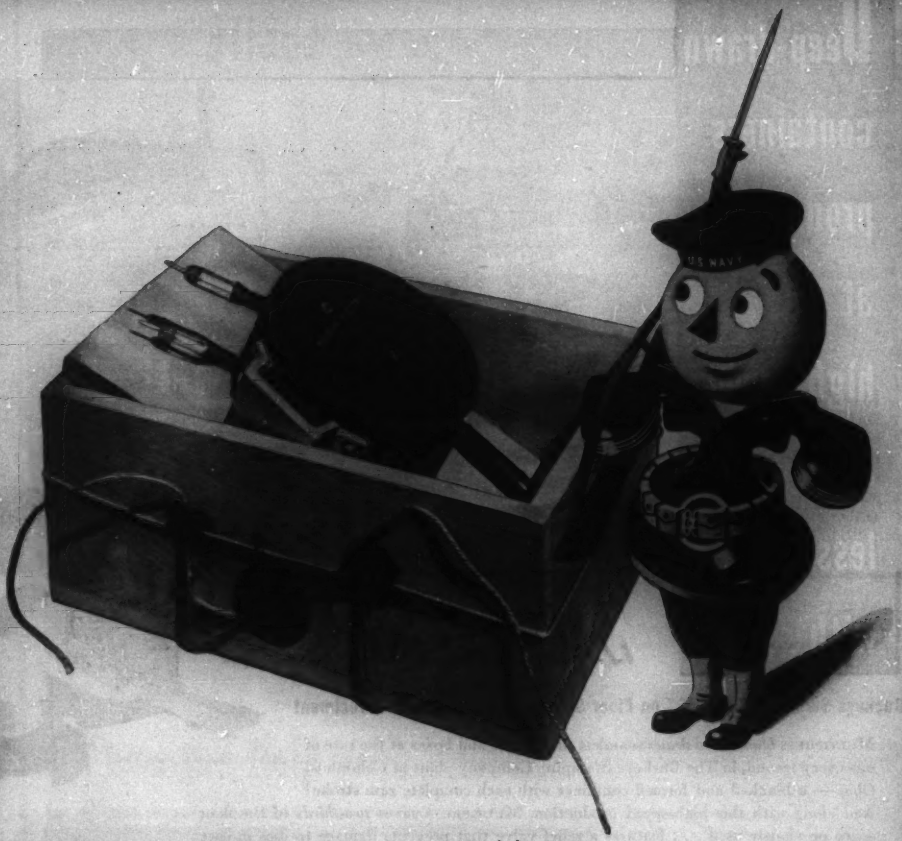

VICTORY REVEALS A MYSTERY

More than two years ago, an engineer of the Laboratories visited *U.S.S. Boise*, returned with a mysterious box which went into the Laboratories' vault. Now, victory opens the box and discloses a special kind of electron tube called a magnetron. It was part of a Radar which furnished data to aim *U.S.S. Boise's* guns during the night action off Savo Island on October 11-12, 1942. Because of the high frequency generated by this magnetron, the Radar was not detected by the enemy and the action was a complete surprise. Six Japanese warships were sent to the bottom of the sea.

This magnetron is a symbol of the Laboratories' enormous war program. Half of it was devoted to Radar, the other half gave birth to radio transmitters and receivers, sonar apparatus for the Navy, loudspeaker systems for ships and beach-heads, fire-control apparatus for anti-aircraft artillery. Coming months will unfold the story of these and many other contributions of the Laboratories to the victory of our arms.

Bell Telephone Laboratories' war work began before the war; until now, it claimed practically all our attention. With victory, we will go back to our regular job—helping to bring you the world's finest telephone service.

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Exploring and inventing, devising and perfecting, for continued improvements and economies in telephone service.

NOW

DU PONT PLASTICS

are available for peacetime use

Here is welcome news for the electrical industry. These Du Pont plastics, after years of use in war products, are now readily available for civilian applications. Speeded by the urgencies of war, research has found new and varied uses for each. Here they are, ready to help you make your product more useful, more attractive, more salable.

Du Pont "LUCITE"

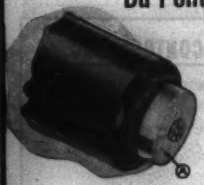
methyl methacrylate resin

Aspherical correcting lens of "Lucite" in new home television set developed by RCA. This lens is produced in a few minutes; the alternative, a glass lens, required hours of skilled polishing. The new lens makes possible a larger and clearer image.

"Lucite" is crystal-clear and light in weight . . . yet strong and durable. It has good dielectric strength, dimensional stability, and excellent optical qualities. In addition to the regular "Lucite" sheets, rods, tubes and molding powder, a new higher heat-resistant "Lucite" molding powder, developed during the war, offers a yield temperature 30° to 40°F. higher than that of other "Lucite" compositions.

Uses: A few of the many uses of "Lucite" are in airport landing lenses, dial facings, knobs, housings and radio insulators. The properties of "Lucite" will make it useful in many radar and other electronic applications.

Du Pont POLYTHENE

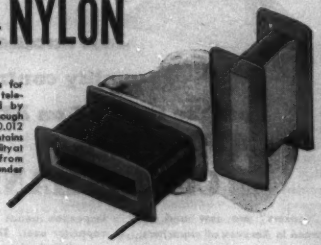


Cross-section (4 2/3 times actual size) of coaxial cable used in television transmission by Allen B. DuMont Laboratories, Passaic, N. J. Polythene's non-polarity is an additional advantage here, since the current sometimes changes direction at 100 million cycles per second. (A) Polythene insulation.

This chemically inert plastic, first developed during the war, offers a unique combination of valuable properties. Polythene has a specific gravity of 0.92. It is admirably suited for insulation of high frequency wire, where its low electrical losses and general physical and chemical characteristics are unequalled by any other material. Polythene is flexible, yet tough, at temperatures ranging from—50°F. to 220°F. It can be injection- or compression-molded, or extruded.

Uses: Polythene has been used to insulate the well-known assault wire used by the Signal Corps.

Du Pont NYLON



Nylon coil forms for sound-powered telephone unit used by U. S. Navy. Although the wall is only 0.012 inch thick, it maintains dimensional stability at temperatures from —60° to 400°F. under low load.

Nylon molding powder, FM-1, new since the war began, is notable for its high heat distortion temperature, unusual toughness and flexibility. It can be injection-molded in thin sections.

Uses: Among the wartime uses of FM-1 nylon were tiny, tough electrical coilforms, valve seats, switch housings for aircraft, and shafts for alignment tools. Nylon often offers a saving in weight and possesses the highest service temperature of the thermoplastics.

Du Pont Engineers will gladly assist you in deciding whether these or other Du Pont plastics can serve your product needs. Address E. I. du Pont de Nemours & Co. (Inc.), Plastics Dept., Arlington, N.J.

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Each and every oil-filled capacitor is examined under ultra-violet or so-called "black" light. The slightest trace of impregnating oil seeping through seams or cracks in containers, shows up as a bright fluorescent spot as the operator peers through the cabinet window. A "leaker" just cannot get by.

Such typical Aerovox quality inspection means much to the oil-capacitor user. The life of such capacitors is dependent upon perfect hermetic sealing. This prevents the entry of moisture. Also, even a slight oil leak might damage or interfere with the operation of associated equipment.

Outstanding quality control—from incoming raw materials through each step in production and on to final inspection—is the final endorsement of Aerovox Capacitor Craftsmanship.

● Submit your capacitance problem

. . . an example of an intricately designed insulator produced in quantity by Universal. Universal porcelain insulators have a high dielectric factor, high compressive strength. They are unaffected by arcing, heat, cold or fumes. They will not corrode, carbonize or oxidize. You can depend on Universal insulators to provide long life and satisfactory performance in your electrical equipment.

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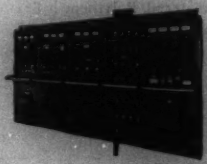
Our experience in packing for the Navy and Maritime Commission puts us in a favorable position to pack for export.



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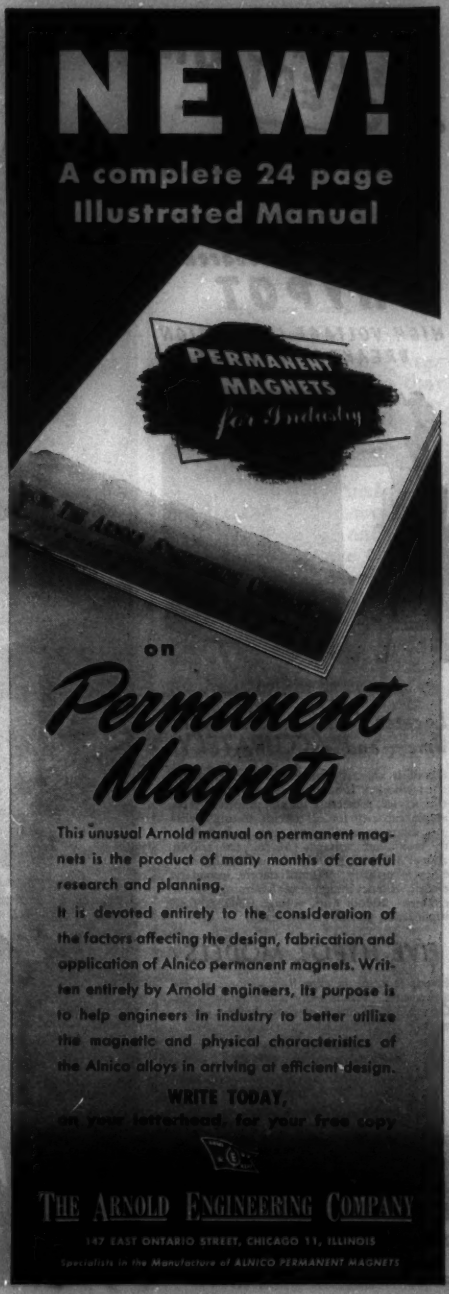
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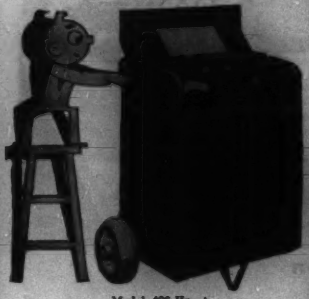
HIGH VOLTAGE INSULATION BREAKDOWN TESTER



Model 406 Hypot

Locates faulty insulation in time—and ACCURATELY!

Hypot is an easily movable unit on rubber-tired wheels. It enables one man to perform this service, protecting life and property. Has ample capacity for all circuit testing, with instantaneous reading on open scale from 0 to maximum voltage. Model 406 shown above: 3 KVA 0-3000-volt secondary, 115-volt 60-cycle primary, 500-milliampere secondary circuit. Comes complete with burning ground circuits. 20-foot high voltage leads, 50-foot input leads, 50-foot ground leads.

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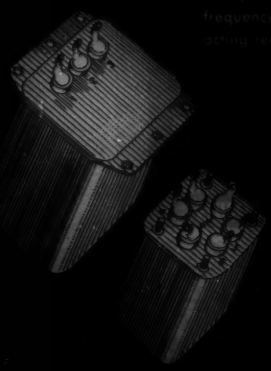

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This convenient No. 759 Kilovoltmeter incorporates several features that make it ideal for either portable or fixed general use. A reversing switch makes it unnecessary to change the terminal connections should polarity be reversed. The built-in meter provides ±2% accuracy and binding posts are provided for an external meter if higher accuracy is required. The meter multiplier section is adjusted within 0.1% so that, when required, more accurate meters may be used with the external connection. This also permits the individual taps of the multiplier to be used as accurate high resistance standards.

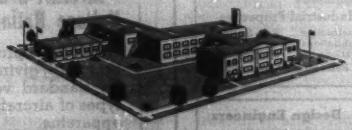
New!
5-RANGE PORTABLE KILOVOLTMETER

1, 2, 5, 10, 20 kilovolts DC at full scale.

Milliohmmeter No. 673-F is a new addition to the growing group of Shallcross direct reading resistance measuring test sets. Linear scales eliminate crowding of the higher resistance values at one end of the scale. Six scales have ranges of 0-0.5-1-5-10-50 and 100 ohms full scale, thus bridging the gap between the regular Shallcross Milliohmmeters that are extensively used for low resistance testing and the ordinary Ohmmeters used for relatively high resistance measurements. Separate connections are provided for current and potential to minimize the effect of lead and contact resistance when measuring low values. The instrument uses a single #6 dry cell battery carried in a compartment.

New!
MEDIUM RANGE MILLIOHMMETER

Six scales: 0-0.5-1-5-10-50 and 100 ohms full scale



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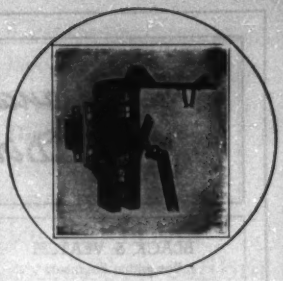

400 Ampere, Catalog 475

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This is their 17th year of successful service. Thousands are in use all over the country. Send for Bulletin

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600 Ampere, Catalog 675

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Men Available

ELEC ENGR; M.S. in E.E. Univ of Minnesota 1938; 30, married. Desires pos elec util; 3 yrs exper in field; 4 yrs with government inspection of aircraft electrical eqpt. E-120.

ASSOC MEM AIEE; 47, married but single status; since 1919 in elec work, both practical and tech; PWR plant operator, chief operator and supt in several hydro-elec stations; electrician, chief electrician and supt in mill, mine, dredging operns; excellent knowl instal, opern, maint of all classes elec eqpt, including re-winding of large and small generators, motors and transformers. Foreign pos only. E-121.

PROF; 45, family; 15 yrs teaching E.E.; 6 yrs Navy service, including officer-instructor Naval Academy; some indus exper; publications; prof degree; 2 masters, pwr, communications; capable head dept. E-122.

ELEC ENGR GRAD; 32; Latin-American; varied exper in rural electrification training; des, instal, opern of Diesel elec plants; indus and residential wiring; small mine opern and management; indus refrigeration instal and opern. Desires pos as engr, sales, constr, opern, des, with util or indus organization in North or South America. Salary open. E-123.

ELEC ENGR; grad; 42, married; 15 yrs des constr and opern communications, indus, general pwr and lighting. Desires permanent connection. E-124.

ELEC ENGR, mem AIEE; 39; 23 yrs elec indus, last 4½ yrs exper indus pwr and lighting distr, electronic motor and sequency control; 4½ yrs temperature automatic recycling control; air, hydraulic, electronic and mech grouping. Desires sales engr, prefer southern Cal, medium size organization. Available immed. E-125.

REG ELEC ENGR; Assoc AIEE; 35. Ten yrs util, overhead distr des, opern, maint and constr; 3 yrs Corps of Engrs, elec distr des, preparation of contract plans, specifications, estimates. Salary and location open. E-126.

ELEC ENGR; 34; 10 yrs exper, indus and marine, des pwr, lighting and communications, trouble shooter hot, cold, sheet and tin mills, large steel co. Desires pos with construction, mining or oil co outside U. S. E-127.

ELEC ENGR; 37; 7 yrs exper—indus plant elec des, constr, instal and maint. Desire pos with elec or constr organiation. E-128.

GRAD ELEC ENGR, Univ of Michigan; 34; 20 yrs util and indus, 3 yrs field eng electronics and gen control, install pwr rectifiers and switchgear. Desire constr or field eng, supt util or indus. Location and travel unlimited. E-129.

LICENSED PROF ENGR; 15 yrs transmission and distr exper on superintendence, maint, des, constr and valuation of elec util systems. Particularly conversant with switching equipment and substations. Terminating duty with armed forces. Affiliation with util co or consulting firm desired. E-130.

ENGR, licensed; writer, editor—specialized in analysing, describing and illustrating projects and eqpt in lucid, accurate, understandable terms; now with War Dept as technical editor; desire connection in New York area. E-131.

ELEC-MECH ENGR; age 43; 22 yrs exper, test inspection, instal, opern, maint of boilers, turbines, elec pwr eqpt. Surveys and reports. Administrative exper. Desires pos as pwr engr, indus or consulting organization, northeast U. S. E-132.

ELEC ENGR; 28, married; B.S. in E.E. at leading Univ. Six yrs exper des, manufacture, test of all types of trans. Salary and location open. Desires permanent pos with util or engg firm in sales or engg capacity. Available immediately. E-133.

EXPER PWR AND UTILIZATION ENGR; age 33; grad, G.E. test, 10 yrs application, des, devpmt switchgear control. Recent Asst Chief Engr. Speaks Spanish. South, West, Foreign preferred. E-134.

MECH ENGR; 26, married; 4 yrs exper prod engg. Phi Beta Kappa. Good personality and health. Engg work involving personal and outside contacts desired or asst to consulting engr. E-135.

ELEC AND MECH ENGR; 29, single; desires permanent pos with m/g firm preferably in greater Boston area. Over 5 yrs exper in factory elec constr and maint. Electrician's license; familiar with automatic controls; good knowl of electronics; 1½ yrs as test and devpmt engr. E-136.

ELEC-MARINE ENGR; 27; 1 yr mech exper pumps, elec-mech devices; 4 yrs des, super marine elec instal, maint; exper pwr, electronic motor control, amplidynes, synchros, amplifiers. Prefer the East. E-137.

ELEC ENGR; young; 4½ yrs mech and elec test and devpmt exper. Desires pos in testing and research with responsibility and future. E-138.

Positions Available

ELECTRICAL ENGINEERS. (a) Electrical Engineers to be trained for patent work in the electronics field, particularly radio. Apply by letter submitting complete details of education, experience and salary requirements. (b) Graduate Electrical Engineer having experience in the preparation and prosecution of U. S. patent applications, preferably in electrical fields, including radio. Apply by letter submitting complete details of education, experience and indicate salary expected. Location, vicinity of New York City. W-5750.

SALES MANAGER for Midwest electrical machinery manufacturer. Specialized equipment. Should have basic engineering training and ability to develop contacts for sales of such products as will be developed. W-5861-D-2451.

ELECTRICAL DESIGNING ENGINEER for manufacture of heavy duty electrical equipment. College graduate, with sufficient designing experience to handle complete A.C. and D.C. motor design, from 100 to 200 hp, independently. Excellent prospects; plant has no conversion problems. Apply by letter stating information or education, experience and salary expected. Location, Middlewest. W-5872C.

GRADUATE ELECTRICAL ENGINEER for permanent position with large utility in distribution engineering work. Experience in overhead or underground distribution desired. Apply by letter stating details of age, education and experience and salary desired. Location, Middlewest. W-5920D.

ENGINEERS. (a) Electrical Engineer, graduate, experienced in design of sub-fractional A.C. and D.C. motors. (b) Mechanical Designers, for small power operated devices. Positions permanent with established manufacturer. Write giving full details, including salary expected. D-2511.

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Capable of designing and supervising installation of equipment. To take complete charge of laboratory and supervise production quality control. Must have previous experience with etching and formation processes.

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• •

Applicants are requested to outline experience, education, present and previous earnings and salary requirements. All replies will be held in strictest confidence. Our own engineers know of this advertisement.

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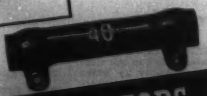

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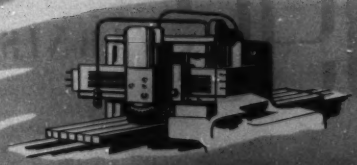

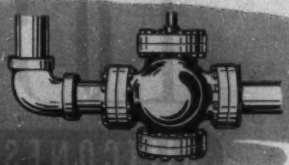

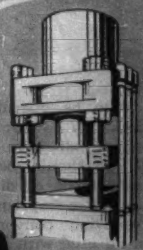

P/R

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Philharmonic Radio Corporation

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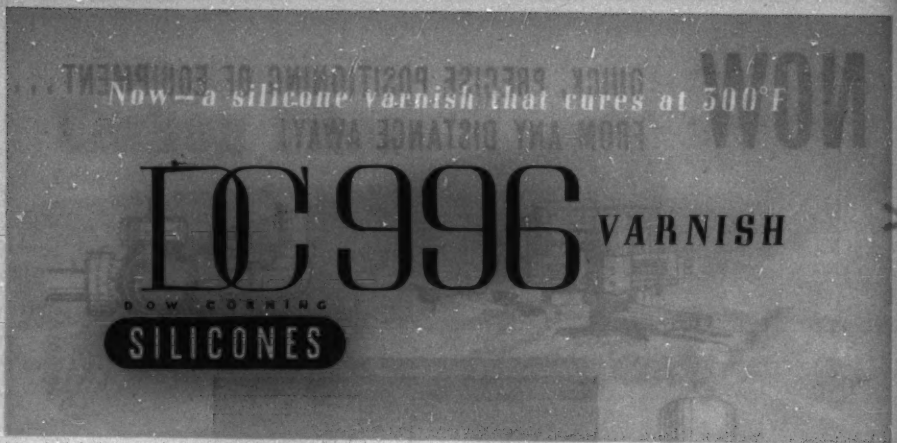

Dow Corning 996 is an electrical impregnating varnish for low temperature baking.

Dow Corning 996 was developed to provide manufacturers of new equipment and rewinders of old equipment with a heat resistant, waterproof silicone varnish which can be cured at temperatures obtainable in ovens now used for curing organic insulating varnishes.

Dow Corning 996 is used as the dipping or impregnating varnish for equipment wound with typical silicone insulation components. These include Fiberglas cloth, tape and sleeving varnished with DC 993; silicone bonded mica-Fiberglas for ground insulation; silicone bonded Fiberglas served magnet wire; silicone-Fiberglas laminated coil separators and slot sticks, and Silastic* coated lead wire.

Electrical equipment, wound with silicone insulating components and sealed by impregnating with DC 996, will have the high order of thermal stability and retention of waterproofness characteristic of silicone insulation.

Dow Corning 996 thus enables all types of electrical shops to realize the advantages of silicone insulation. It is recommended for use in equipment which is to be operated at temperatures up to 175°C. (347°F.). For higher operating temperatures, or extremely severe service conditions, DC 993 should be used throughout. The same methods of dipping, spraying, or vacuum-pressure impregnating that are used for applying conventional organic varnishes can be used with DC 996.

PROPERTIES—Dow Corning 996 is furnished as a 50 per cent by weight solution in an aromatic solvent and has a viscosity of 2 to 5 poises. In this consistency DC 996 is suitable for impregnating electrical equipment. It can be reduced to any desired viscosity with aromatic naphtha.

Dow Corning 996, when coated on metal, air dries to a slightly tacky, soft film. Baking the coated panel at 150°C. (302°F.) for a period of four hours will cure the coating to a non-flowing, tack-free, flexible film. DC 996 has ample heat stability for continuous use at temperatures as high as 175°C. or for intermittent use at higher temperatures.

ELECTRICAL PROPERTIES OF DC 996—(measured on coated panels at 25°C. and 50% relative humidity.)

Dielectric Strength, volts per mil	1500 to 2000
Dielectric Constant, at 1000 cycles	3.0
Power Factor, at 1000 cycles	0.7%

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* Trade name for Dow Corning Silicone Rubber

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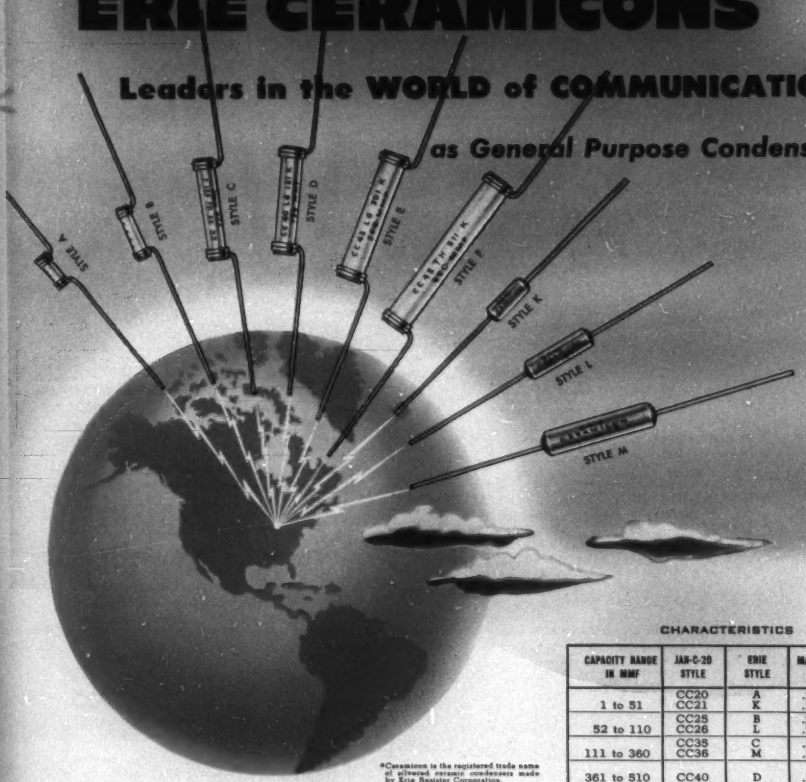

*Ceramicons is the registered trade name of silvered ceramic condensers made by Erie Resistor Corporation.

CHARACTERISTICS

CAPACITY RANGE IN MMF	JAN-C-20 STYLE	ERIE STYLE	MAXIMUM OVERALL DIMENSIONS
1 to 51	CC20 CC21	A K	.200 x .400 .250 x .562
52 to 110	CC25 CC26	B L	.200 x .656 .250 x .812
111 to 360	CC35 CC36	C M	.265 x 1.125 .340 x 1.328
361 to 510	CC40	D	.375 x 1.110
511 to 820	CC45	E	.375 x 1.560
821 to 1100	CC45	F	.375 x 2.00

CHOICE OF TEN STANDARD TEMPERATURE COEFFICIENTS

THE superior stability and performance of Erie Ceramicons have steadily increased the popularity of these silvered ceramic condensers since their introduction, now almost ten years ago. Today, they are literally leaders in the world of communications.

Strenuous war conditions have emphasized the necessity for equipment of unfailing reliability, and Erie Resistor has been called upon to furnish millions of Ceramicons, particularly as general purpose condensers, where a moderate degree of capacity change with temperature is permissible.

The superiority of Erie Ceramicons as general purpose condensers for home receivers and civilian communications equipment, has been proved in numerous applications. They are ideal coupling condensers, as in plate-to-grid installations, where high insulation resistance is imperative.

Ceramicons may be selected from any one of 10 standard temperature coefficients, ranging from P120 to N750.

The capacity range for equivalent physical size is given in table above. We will gladly send you samples of Erie Ceramicons for your general purpose applications.

Electronics Division

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- ★ *Washing machines*
- ★ *Vibrators*
- ★ *Sewing machines*
- ★ *Food mixers*
- ★ *Floor waxers*
- ★ *Electric trains*
- ★ *Kitchen ventilators*
- ★ *Oil burners*
- ★ *Stokers*

No QUESTION about it—your big money in sales is coming from appliances that won't set up local interference in radio and television receivers.

When the big rush for the new radios begins, your customers—better informed than ever before—are going to demand noise-free performance in shavers, vacuum cleaners, oil burners, refrigerators, mixers—in *all* motorized appliances. You can count on *that.*

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